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METHODS AND SPECIMENS FOR COMPARATIVE INVESTIGATIONS OF FATIGUE RESISTANCE OF PARTS WITH MULTILAYER SURFACING

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The design of specimens and methods for experimental evaluation of fatigue life of multilayer deposited specimens at the cyclic mechanical loading were developed. The design of specimens simulates the design of real deposited parts, which allows performing a comparative evaluation of influence of chemical composition of the base metal and deposited layers, as well as technique and technology of surfacing separate beads or layers on their fatigue life. For investigations of fatigue life of specimens, the appropriate loading schemes were chosen, which with certain assumptions reproduce cyclic power loads characteristic for real parts: large-modulus gears, pressing screws of rolling mills, mill rolls, MCCB rollers, etc. The results of experimental investigations of the cyclic fatigue life of specimens according to the proposed methods are given. It was established that the developed investigation methods should be used for evaluation of the fatigue life of different parts when selecting materials, equipment and technology of restoration or manufacturing multilayer surfacing. 11 Ref., 1 Table, 8 Figures.

Keywords: *arc surfacing, multilayer surfacing, fatigue testing methods, fatigue, cyclic fatigue life, design of multilayer specimen*

Indices of fatigue life are one of the most important characteristics of deposited parts, operating under cyclic load conditions. This problem is particularly acute when restoring worn parts by surfacing methods. These parts have already passed a certain period of operation and exhausted a part of the life margin preset during their designing and manufacturing. When selecting surfacing materials and developing the technology of restoration surfacing of such parts, it is necessary to evaluate the effect of preliminary operating time on the residual service life of a restored part.

At present, there are no generally accepted methods for testing fatigue life of deposited specimens under cyclic mechanical loads. Standardized methods of testing fatigue life [1–3] are difficult for adaptation to the operating conditions which are typical for many of the deposited parts, since the specimens used in these methods have either a cylindrical solid (thickness of up to 25 mm) or hollow (wall thickness of 2 mm) section, or they represent flat specimens of up to 10 mm thickness. The specimens of such a shape and small dimensions do not allow investigating the influence of chemical composition of surfacing materials and structures of deposited layers in multilayer deposited specimens on their cyclic fatigue life. Using the standard specimens it is also impossible to evaluate the influence of specifics of the performance of repair-restoration and manufacturing surfacing on the characteristics of fatigue life resistance of parts. As a result, the tests are usually carried out in specialized experimental installations, on specimens of different design which rarely simulate the operation of full-scale parts during their service, which leads to the results, which differ significantly for the same material and surfacing technology [4–8].

It should be noted that during surfacing of some parts, for example, mill rolls, dies, BCCM (billet continuous casting machine) rollers, etc., surfacing materials are used, which provide producing the deposited metal of the type of tool steels of a sufficiently high hardness (*HRC* > 45) and wear resistance. A high hardness of the deposited metal greatly complicates the technology of manufacturing the appropriate specimens for fatigue tests, requiring a complete heat treatment cycle. At the same time, under the production conditions, the parts after surfacing, as a rule, do not pass a complete heat treatment and, therefore, it is only indirectly possible to judge about a cyclic fatigue life of deposited parts.

The aim of this work is to develop the design of specimens and methods of comparative investigations of the fatigue resistance of parts with multilayer sur-

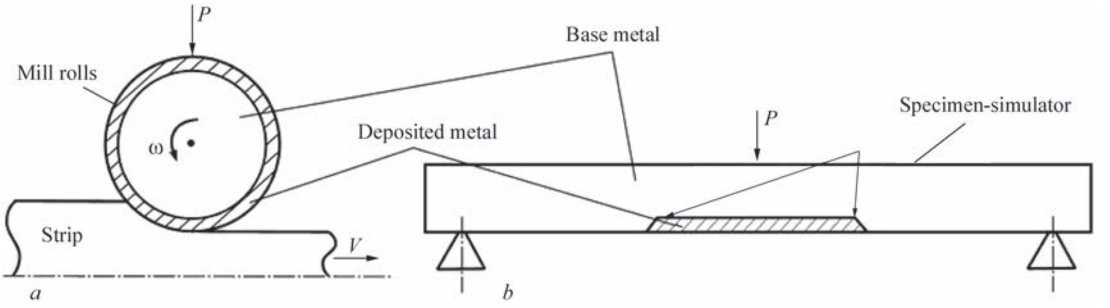

Figure 1. Scheme of strip rolling (*a*) and specimen-simulator loading according to the three-point bending scheme (*b*). Arrows indicate the transition from base metal to deposited one

facing, which will take into account the influence of chemical composition of the deposited layers, their geometric dimensions and the technology of surfacing and cyclic fatigue life.

For fatigue tests of welded or deposited specimens, tension, pure or circular bending is used [4, 6–9]. Based on the conditions of operation of parts of metallurgical equipment and some other parts requiring repair using surfacing, it is advisable to carry out tests at cantilever or three-point bending of specimens [4]. All the parts of the machines mentioned in this article can be divided into two groups: simple (mill rolls, BCCM rollers, etc.) and complex (gears, buttress thread, etc.) shapes.

Group 1. For the specimens, simulating deposited parts such as mill rolls, BCCM rollers, etc., it was proposed to use loading of specimens according to the scheme of three-point bending with application of from zero cyclic load on the specimen centre (Figure 1). Tests according to this scheme reproduce the power loads characteristic of these parts with a certain assumption and, in addition, in the process of testing, it is possible to conduct a visual evaluation of the rate of a fatigue crack propagation. When selecting the dimensions of the specimen, it is necessary to take into account the influence of the scale factor on the characteristics of fatigue resistance, i.e., the width of the specimen should be selected based on the condition of preserving uniaxial stressed state at all points of the specimen [1].

The shape and dimensions of the specimens for fatigue tests should be preset not only on the basis of the abovementioned requirements, but also on the assumption that the specimen should sufficiently simulate a deposited multilayer structure of a real part. Since surfacing on the specimen is performed only on one side, then its dimensions should be such that the deformation of the specimen after surfacing was minimal. Based on the available experience [10, 11] and the results of preliminary experiments, a design of prismatic specimens (in the shape of a rectangular parallelepiped) was developed, having dimensions of 20×40×300 mm with a groove for surfacing of 150 mm width and 10 mm depth (Figure 2).

When it is necessary to manufacture specimens that differ in geometrical parameters from the specimens shown in Figure 2, to calculate the dimensions of the groove for surfacing, it is recommended to use the results of the work [10]. The main requirement is the places of transition from deposited to the base metal (indicated by arrows in Figure 1, *b*) which should not be a potential place for initiation of fatigue cracks due to being too close to the place of application of the outer load.

To evaluate the cyclic fatigue life of the parts, the deposited metal of which has high hardness (*HRC* 46–50), the following technology was developed for the manufacture of specimens. Semi-products with a small tolerance for subsequent machining are assembled in a pack using technological inserts

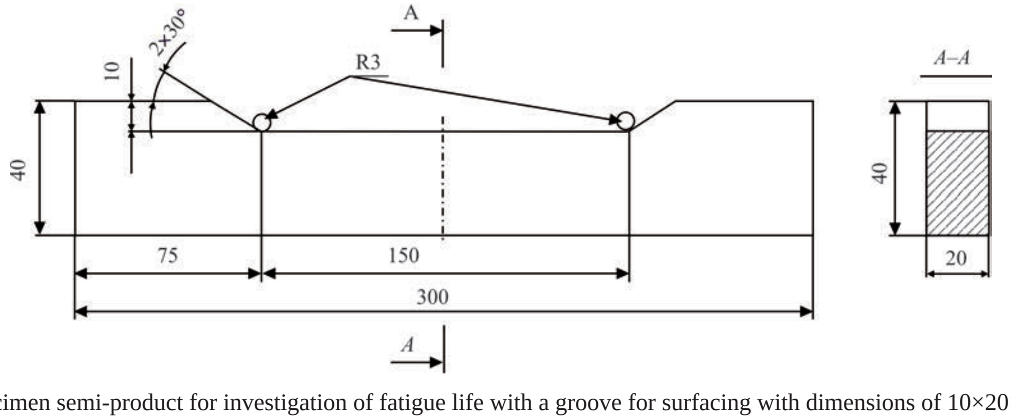

Figure 2. Specimen semi-product for investigation of fatigue life with a groove for surfacing with dimensions of 10×20×150 mm

of 5 mm thickness. On the sides of such a pack, run-out tabs are welded-on and automatic arc multilayer surfacing of the packages is performed (Figure 3). After that, the deposited pack of semi-products is cut by abrasive discs through technological inserts into separate semi-products and the metal layer, overheated during the cutting process, is removed in the grinding machine (during the machining of specimens, their heating above 50 °C is not allowed). After finishing grinding of all four sides, the specimens are ready for fatigue tests. This specimen manufacturing technology provides preserving of their transverse dimensions and does not allow any curvature along any axis, providing surface roughness by the class 9–10 according to GOST 2789–73.

Group 2. For the specimens, simulating deposited parts of a complex shape (teeth of large-modulus gears, large threading of pressing roll mill screws, buttress threading of suspended cones of conic crushers, crankpins, etc.), the design of specimens was developed, taking into account the features of wear and application of power loads in the parts of this group. In such parts, the wear zone and the application of cyclic load do not coincide with the zone of the most probable occurrence of fatigue damages (Figure 4, *a*, *b*). For example, the friction forces, occurring in the process of gears operation, lead to their wear and formation of cavities along their polar line (Figure 4, *b*). Moreover, during operation, cyclic stresses reach maximum values at the root of the tooth, and the zone of maximum wear is located higher. In addition, the transition from the tooth root to the cavity is a stress concentrator [10].

In practice, two schemes for surfacing a tooth are possible: the first one is restorative (Figure 5, *b*), the aim of which is the surfacing of only a worn area; the second is restorative-hardening (Figure 5, *c*), the aim of which is not only to restore the shape of the tooth, but also to apply a deposited metal to replace a damaged part of the material in the stress concentration zone at the base of the tooth.

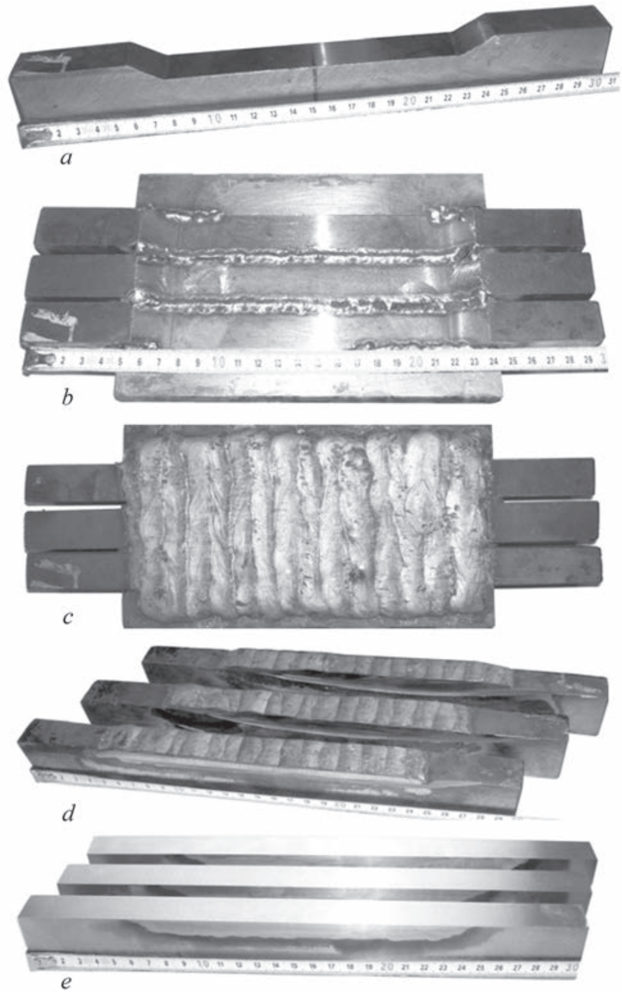

Figure 3. Stages of manufacturing deposited specimens: semi-product with a groove for surfacing (*a*); semi-products, assembled into a pack (*b*), after surfacing (*c*), cutting (*d*) and finishing grinding (*e*)

A characteristic feature of these schemes is a significant difference in the distribution of residual stresses after surfacing, which can have an impact on the life of a deposited part. Thus, if only a worn area is deposited and only a shape of the tooth is restored, then tensile welding stresses can significantly reduce the fatigue life of a restored part. Restoration of geometrical dimensions of worn parts without eliminat-

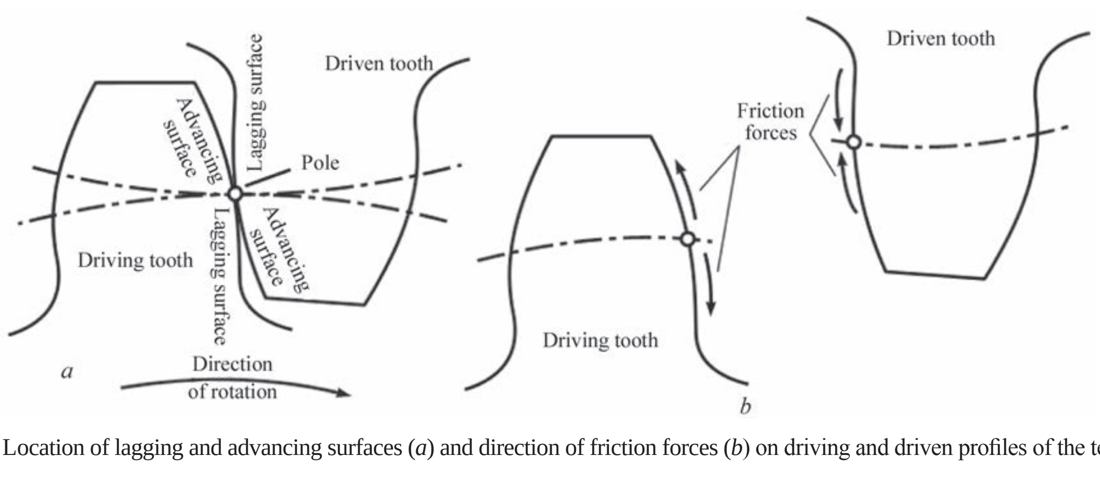

Figure 4. Location of lagging and advancing surfaces (*a*) and direction of friction forces (*b*) on driving and driven profiles of the teeth [10]

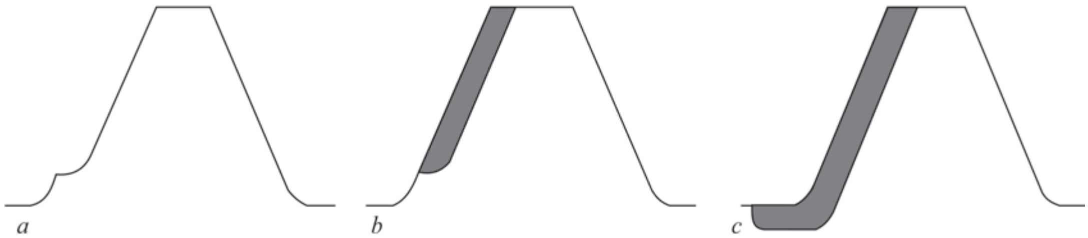

Figure 5. Shape of worn tooth (*a*) and possible schemes of its surfacing: *b* — restoration of initial dimensions of a tooth (scheme 1); *c* — restoration-strengthening surfacing with a replacement of damaged material in the stress concentration zone near the tooth root (scheme 2)

ing fatigue damages outside the wear zone does not give the positive results [10].

Based on the fact that a fracture of the gear tooth occurs due to the formation of a fatigue crack near its base, for experimental evaluation of fatigue life, a design of specimens was developed having a similar stress concentrator (Figure 6). The size of the transition radius in the specimens is selected based on the determining dimensions of teeth of real large-modulus gears. Fatigue tests, taking into account the application of real loads on the part, should be carried out at from zero cantilever bending.

Depending on the used scheme of surfacing (see Figure 5) for fatigue tests, the following specimens were manufactured: with a stress concentrator (Figure 7, *a*), with a groove for surfacing according to the scheme 1 (Figure 7, *b*) or with a groove for surfacing according to the scheme 2 (Figure 7, *c*).

The developed designs of specimens and testing methods were tested during investigation of fatigue life of materials used for surfacing the parts of metallurgical equipment, which are made of medium and high-carbon unalloyed or low-alloyed structural steels of type 35KhM, 40Kh, 50 Kh, 50KhN, etc. Two batches of specimens were manufactured, respectively, for the study of cyclic fatigue life of parts of simple (mill rolls, etc.) and complex (teeth, etc.) shapes.

The first batch of specimens (see Figure 2) consisted of three series (three specimens in each series) for tests according to three-point bending scheme (see Figure 1, *b*). The first series of specimens of steel 40Kh was tested in the initial state (without surfacing); the specimens of the second series — after surfacing using flux-cored wire PP-Np-25Kh5FMS with a diameter of 2.0 mm under the flux AN-26P (surfacing mode: voltage is 24–26 V; current is 230–250 A; rate of surfacing is 20 m/h); the specimens of the third series — after surfacing and at the same modes of the intermediate layer using the solid wire Sv-08 of 2.0 mm diameter under the flux AN-348A and after the subsequent surfacing using the flux-cored wire PP-Np-25Kh5FMS under the flux AN-26P.

The second batch of specimens (see Figure 7) consisted of four series (three specimens in each series) for testing according to the scheme of cantilever bending (see Figure 6). The first series of specimens of steel 35KhM was tested in the initial state (without surfacing); the specimens of the second series — after

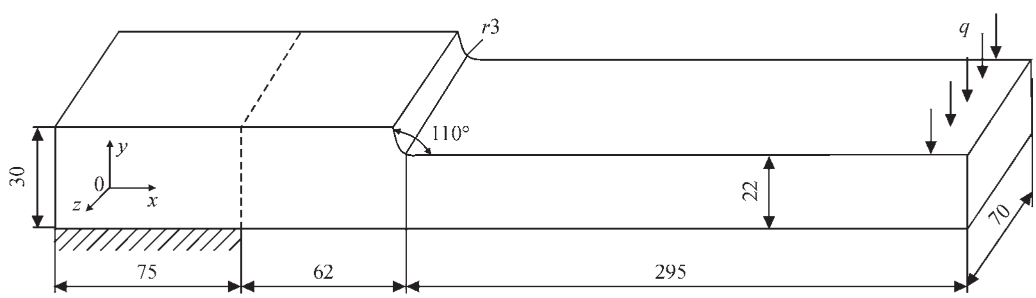

Figure 6. Scheme of loading the model specimen for investigation of cyclic fatigue life of a gear tooth (*q* — applied from zero cyclic outer loading)

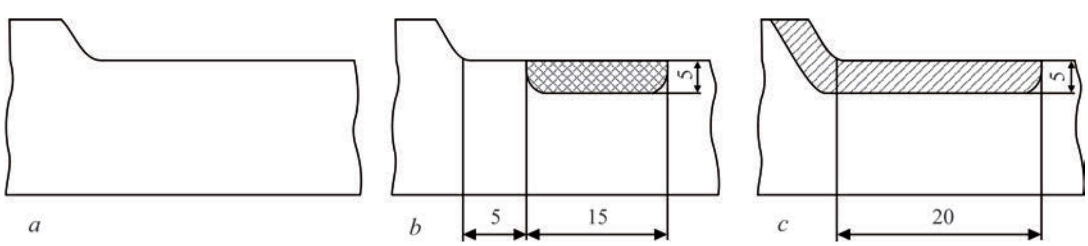

Figure 7. Schemes for performing restorative surfacing of specimens for fatigue tests: initial (*a*); with preparation for surfacing according to the scheme 1 (*b*) and with a groove for surfacing according to the scheme 2 (*c*)

Results of tests of fatigue life of specimens under cyclic mechanical loading

Specimen type and dimensions	Specimen material	Number of cycles before appearance of cracks in specimens			Average number of cycles before crack appearance
		1	2	3	
Specimens with dimensions of 20×40×300 mm for testing under the three-point bending (Figure 2)					
Solid specimen without preparation and surfacing	Steel 40Kh	190500	199750	215300	201850
With surfacing without sublayer	Steel 40Kh + 25Kh5FMS	120100	134300	124800	126400
With surfacing with sublayer	Steel 40Kh + 08kp + 25Kh5FMS	179300	165100	180600	175000
Specimens with dimensions of 30×70×432 mm for testing according to the scheme of cantilever bending (Figure 7, *a–c*)					
Solid specimen without preparation and surfacing	Steel 35KhM	185700	176900	178900	180500
With preparation and surfacing according to the scheme 1	Steel 35KhM + Np-30KhGSA	111350	126800	134450	124200
With preparation and surfacing according to the scheme 1*	Same	17200	20100	18800	18700
With preparation and surfacing according to the scheme 2*	»	214800	220100	234700	223200
*Specimens before preparation and surfacing were loaded for 10^5 cycles.					

surfacing using the solid wire Np-30KhGSA with a diameter of 2.2 mm under the flux AN-26P according to the scheme 1 (surfacing mode: voltage is 32 V; current is 300 A; deposition rate is 18 m/h); the specimens of the third series — after preliminary operating time of 10^5 cycles and the subsequent preparation and surfacing using the solid wire Np-30KhGSA with a diameter of 2.2 mm under the flux AN-26P according to the scheme 1 (surfacing mode: voltage is 32 V; current is 300 A; deposition rate is 18 m/h); the specimens of the fourth series — after a preliminary operating time of 10^5 cycles and the subsequent preparation and surfacing using the solid wire Np-30KhGSA with a diameter of 2.2 mm under the flux AN-26P according to the scheme 1 (surfacing mode: voltage is 32 V; current is 300 A; deposition rate is 18 m/h).

The calculation of ultimate loads and a number of cycles before fracture was selected from the following prerequisites. As far as the tests had a comparative nature, then to shorten a period of tests, a relatively small number of cycles was selected: $2\cdot10^5$ [11]. A calculation of loads was carried out which could provide such a number of cycles until a fatigue crack appeared in the specimen. For specimens of steels 40Kh and 35KhM, to this number of cycles the maximum number of applied stresses equal to 500 MPa is corresponded. The test results of two batches of specimens are given in the Table.

In the process of tests, each specimen is under the constant visual control (inspection is every 15–30 min), during which the side polished etched surfaces of the specimen are lubricated with kerosene to reveal the location of crack initiation. The test report records the number of specimen loading cycles until one or several cracks with a length of 1.0–1.5 mm appear, after which the tests are stopped. For example, Figure 8 shows the outer appearance of the specimen with fatigue cracks.

Tests of specimens (Table), made of base metal without and with surfacing, confirmed the reasonable accepted design loads and showed that the developed methods and specimens can be successfully used for comparative evaluation of fatigue life of deposited parts. The obtained experimental results clearly illustrate the influence of the chemical composition of surfacing materials, the structure of deposited layers and the surfacing scheme on the cyclic fatigue life of the specimens.

The cyclic fatigue life of specimens of the first type of steel 40Kh with a deposited wear-resistant layer such as steel 25Kh5FMS decreased by about 38 % as compared to the cyclic fatigue life of specimens of the base metal without surfacing. Deposition of the underlayer of plastic material (of type of low-carbon steel 08(semi-killed)), provided a significant (approximately by 38 %) increase in the cyclic fatigue life as compared to the specimens, deposited without an un-

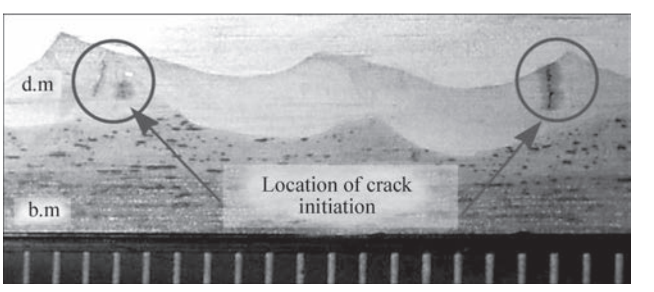

Figure 8. Outer appearance of the side surface of the specimen with the areas where fatigue cracks initiated: b.m. — base metal; d.m — deposited metal

derlayer. The decrease in life as compared to non-deposited specimens in this case does not exceed 14 %.

As follows from the data of the Table, fatigue tests of specimens of steel 35KhM simulating the teeth of large-modylus gears showed that preliminary cyclic fatigue life for 10^5 cycles has a significant effect on the life of deposited specimens, since it leads to accumulation of fatigue damages in the area of stress concentrator at the tooth root. The performance of restoration surfacing according to the scheme 1 without removing the base metal, that has fatigue damages, is impractical because it actually leads to a significant reduction in the residual cyclic fatigue life. The performance of restorative-hardening surfacing according to the scheme 2, with the removal of a damaged metal layer near the stress concentrator, allows even 1.2 times increasing the residual fatigue life of the teeth restored by surfacing as compared to the initial state.

Conclusions

1. The designs of multilayer deposited specimens and corresponding methods for evaluation of their fatigue life under cyclic mechanical loading were developed. These methods and specimens allow carrying out a comparative evaluation of the effect of multilayer surfacing, chemical composition of deposited layers, their thickness, technology and technique of surfacing on the fatigue life of deposited parts.

2. During approbation of the methods, it was found that the use of a low-carbon steel of type 08(ps-killed) as an underlayer in wear-resistant surfacing of specimens of steel 40Kh, simulating operating conditions of mill rolls allowed increasing their cyclic fatigue life by 38 % as compared to specimens produced without underlayer. The similar results were obtained when testing specimens, simulating operating conditions of the teeth of large-modulus gears. Performing surfacing and removing the damaged layer of the base metal allows 1.2 times increasing the life of the teeth restored by surfacing as compared to the initial state.

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