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STRUCTURAL DEGRADATION AND DAMAGE CAUSED BY A SYSTEM OF CRACKS TO THE STEEL OF METALLURGICAL EQUIPMENT

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We develop an automated method for the quantitative analysis of a system of cracks aimed at the diagnostics of the state of rollers in the machines for continuous casting of blanks. A structural methodology of the identification of cracks is proposed and the efficiency of detection of cracks on the basis of computer processing of digital images is demonstrated. We also compare the parameters of a system of cracks on the oxidized surfaces of rollers when the outer layer is removed.

Keywords: cracks, system of cracks, analysis of the images, diagnostics of cracks.

The operation of machines for continuous casting of blanks (MCCB) under the conditions of thermomechanical loading leads to the multiple cracking of the surfaces of rollers. The initiation and merging of a system of cracks affect the energy of deformation of the surface layers of materials and cause the effect of self-organization of multiple cracking, i.e., the formation of macroscopic dissipative cracked structures [1–6]. Thus, it is necessary to develop and improve the methods aimed at the operative diagnostics of the state of surfaces in the case of multiple cracking with regard for the degradation of the material in local areas, changes in its structure, and exhaustion of its plasticity [3].

The existing methods only partially reflect the regularities of multiple cracking under the conditions of thermal fatigue, and the influence of operational factors on the accuracy of rapid diagnostics is studied insufficiently [5–7]. Thus, in particular, as a result of intense external cooling and contact with a slab blank, the surface of the roller is covered with an oxide layer, which complicates its diagnostics and makes it necessary to remove a thin surface layer [1, 3].

In the present work, we analyze the degradation of the material of the surface layers of rollers of the MCCB and improve the procedure of detection and description of the parameters of systems of multiple cracks.

Procedure of Assessment of Structural Degradation and Multiple Cracking

We study a fragment of an MCCB roller made of 25Kh1M1F steel. The roller was removed from operation at the “Illich Integrated Iron & Steel Works” (Mariupol) due to the appearance of cracks on its working surface as a result of thermal fatigue caused by periodic contacts with the metal heated to a temperature of 1100–1200°C followed by cooling in the atmosphere of water vapor. The temperature of its surface varied within the ranges 450–670°C in the contact zone and 100–375°C in the cooling zone [1]. The specimens were cut out from the roller to guarantee the possibility of analysis of its structure in the zone of thermal cyclic loading *A* (Fig. 1) at a depth of up to 5 mm from the outer surface. For this purpose, we used an Axiovert-40MAT metallographic microscope (Carl Zeiss).

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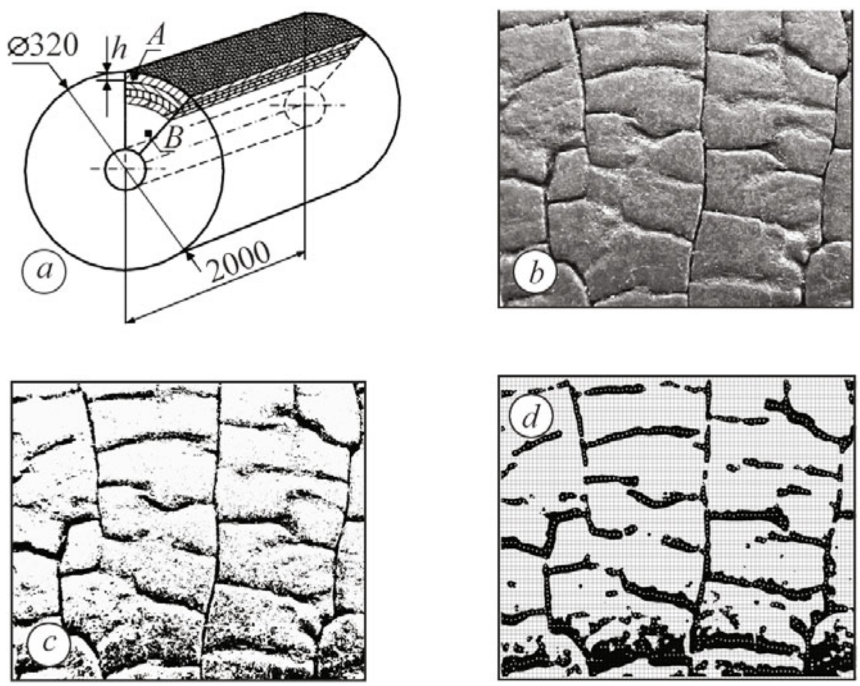

Fig. 1. Analysis of the cracked surface of the MCCB roller: (a) schematic diagram of cutting out the specimen, (b, c) original and binary images of the cracked surface, respectively, (d) fragment of the recognized image.

In addition, the structure of the material was analyzed outside the zone of thermomechanical influence (in zone *B*) at a depth of 50.0 mm from the surface of the roller. The specimens were preliminarily treated in a Buehler-Beta grinding-and-polishing machine and etched in a mixture of nitric and hydrochloric acids.

Since the presence of multiple cracking requires the analysis of the geometry of a great number of defects, its basic regularities are studied on the basis of the numerical analysis of digital images of the roller surface [5–8]. The black-and-white photographic images of cracked structures are analyzed according to the algorithm developed in [8–10], which enables us to identify the structural parameters (the number and orientation of cracks and the fraction of surface cracking). The accumulated results are in good agreement with the data of macroanalysis of the roller surface [1, 3]. The quantitative parameters of the system of cracks (length and direction of propagation) are estimated for different distances from the roller surface.

Structural Degradation of the Material

In the intact state, the structure of 25Kh1M1F steel is ferritic-pearlitic with clearly pronounced grain boundaries (Fig. 2a). After operation, the material of the surface layer of the roller at depths of up to 5.0 mm is characterized by the presence of scattered defects and fuzzy interphase boundaries. In the bulk of ferritic grains and on their boundaries, the carbide particles become spheroidal (Fig. 2b).

The exhaustion of plasticity of the material promotes the initiation and coalescence of microdefects in several slip planes which, in turn, leads to multiple crack formation [10, 11]. The analysis of metallographic sections of the subsurface layers performed with the help of an optical microscope shows that the structure of the material in the vicinity the fatigue crack is similar to the structure of the surface layer of the roller (Figs. 2b and d). We also reveal a zone of accumulation of local strains in the vicinity of the crack front (see Fig. 2c).

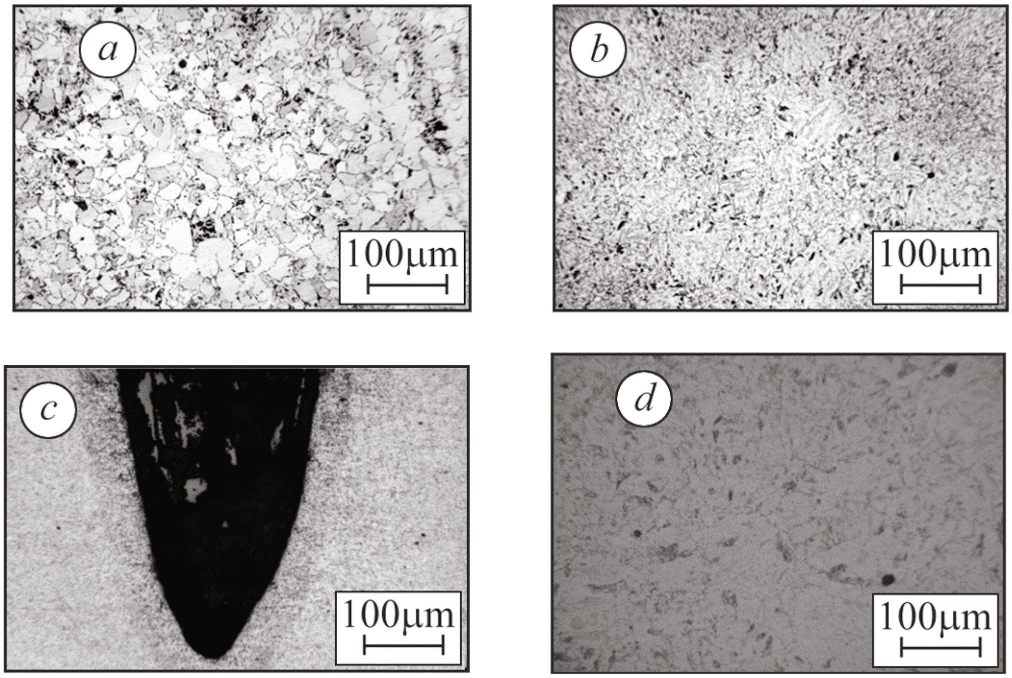

Fig. 2. Structures of 25Kh1M1F steel (×200) in the intact (a) and degraded (b–d) states.

Analysis of the System of Thermal Fatigue Cracks

The outer surfaces of the specimens were milled with steps of 0.4 mm in order to detect the changes in the direction of propagation of the system of cracks. The cracked surfaces were photographed and the initial (half-tone) images were transformed into black-and-white (binary) images. These images were regarded as a discrete approximation of the characteristic functions of the analyzed object or as a statistical geometric model of the cracked structure. After the transformation, the analyzed structural elements (contours and sizes) were reproduced in black against the white field of the matrix. Each image and binary picture contained at least 100 objects representing a statistically significant data array [8].

The scaling reproducibility of the location and sizes of the cracks reveals the presence of structural formation under the conditions of self-organization typical of inhomogeneous media. The elements of the digital matrix enable us to describe the structural transformations of the system of cracks in the course of operation [9]. It is shown that, for all studied situations, more than 70% of cracks are oriented in mutually perpendicular directions ($\theta = 0.90°$) (Fig. 3).

The oxidation of the roller surface almost does not affect the relative fraction of cracking $\nu = F_T / F$, where F_T is the total area occupied by the cracks in the analyzed zone of metallographic section and F is the area of the investigated part of the metallographic section [8]. Thus, $\nu = 8\%$ on the surface. At the same time, at depths of 1.2 and 1.6 mm, it is equal to 8 and 9% respectively (Fig. 4a). The increase in this parameter to 20% at a depth of 0.4 mm and its subsequent decrease to 14% at a depth of 0.8 mm are explained by the incomplete removal of the surface oxidized layer and the identification of fatigue cracks with neighboring crack edges as a part of the cracked structure.

We also analyze the number of “combined cracks” in the entire family of cracks. Thus, if any two individual cracks have at least one common point, then they are regarded as combined.

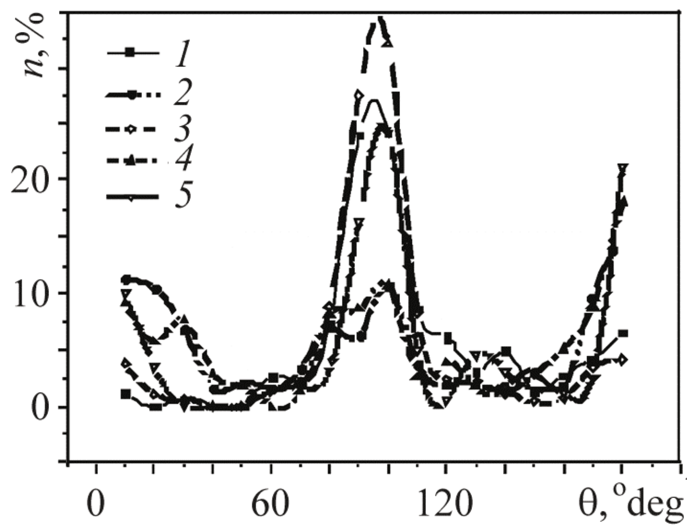

Fig. 3. Predominant orientation of thermal fatigue cracks in the analyzed zone of the roller surface (1) and at depths of 0.8 (2), 1.2 (3), 1.4 (4), and 2.0 mm (5).

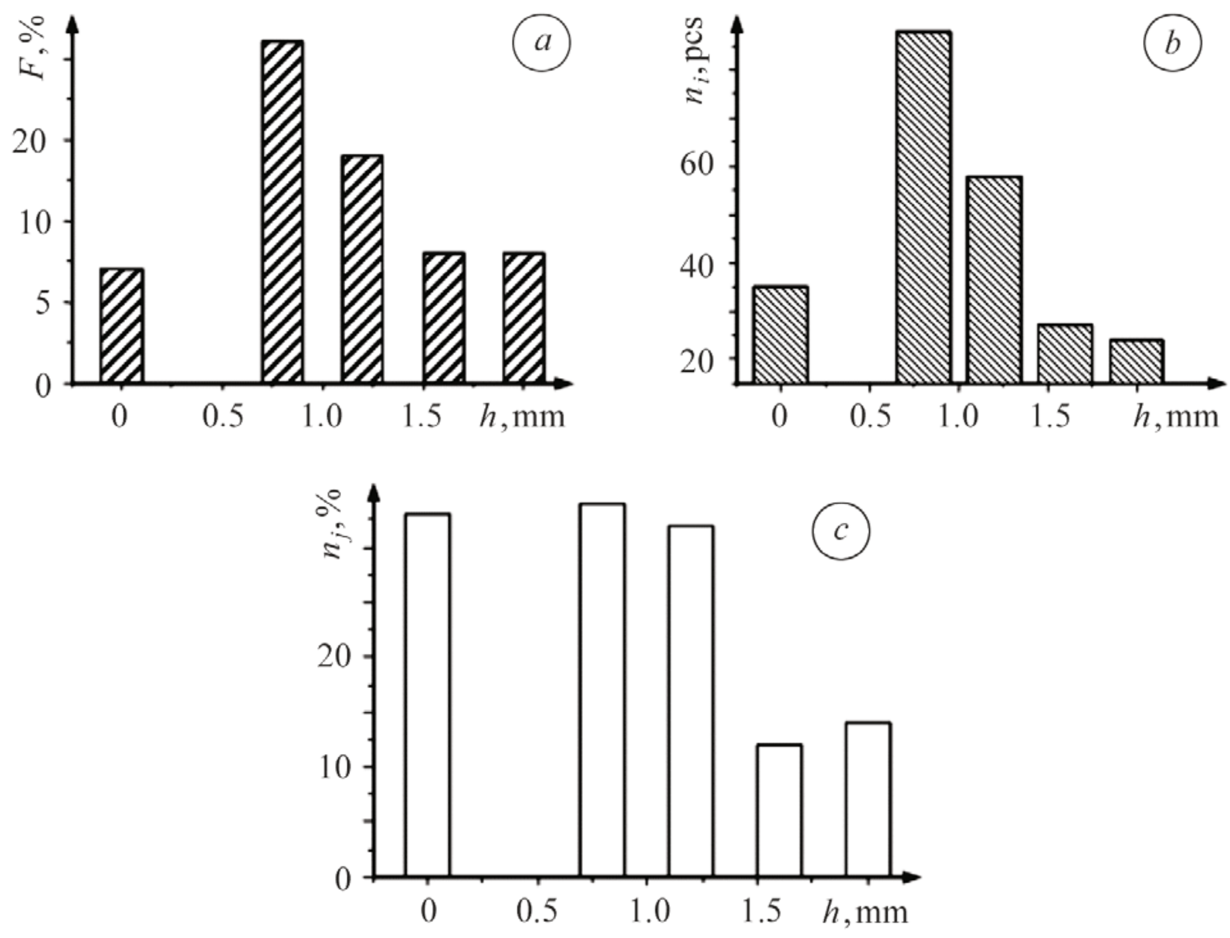

Fig. 4. Parameters of cracking at different distances from the roller surface: (a) relative area occupied by the cracks (%), (b) number of detected cracks (pcs), (c) number of combined cracks, %.

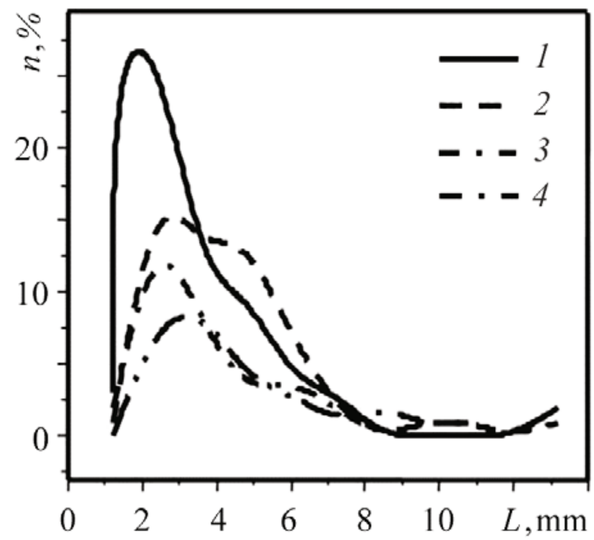

Fig. 5. Distributions of the number of detected cracks over the surface of the roller (1) and at the analyzed depths: (2) 0.4, (3) 0.8, (4) 1.2 mm.

The numbers of cracks of this sort (n_j) detected on the surface and at a depth of 0.8 mm are constant. This means that the analyzed parameter is stable even on the oxidized surface (Figs. 4b and c). This is explained by the fact that coalescence is mainly observed for the longest cracks well identified under the proposed conditions [12, 13]. At depths of 1.2–1.6 mm, the specific fraction of combined cracks decreases from 30 to 13–15%. This is explained by the geometry of the crack. Indeed, they are almost round down to a depth of 4.0 mm but become semielliptic at larger depths [1].

In the investigated part of the roller surface, we discovered 35 (15%) individual cracks. If a thin surface layer is removed by grinding (in the case of incomplete removal of oxidized surface domains near the cracks), then the number of cracks rapidly increases. At a depth $h = 0.8$ mm and in deeper layers, the number of revealed cracks monotonically decreases as a result of the removal of the most cracked layer. We analyze the distributions of crack lengths L on the surfaces located at various depths h (Fig. 5). Thus, the lengths of the maximum number of cracks $L = 2.0$–3.0 mm, and the length of the deepest cracks is equal to 13.0 mm.

In conclusion, we note that the developed original method can be efficiently used for the rapid diagnostics of degradation of the surfaces of rollers of the MCCB, as well as for the evaluation of the parameters of cracking and directions of crack propagation [13].

CONCLUSIONS

We study the mechanisms of deformation preceding multiple cracking of the surfaces of rollers of MCCB. Under thermomechanical loading, the boundaries of ferritic and pearlitic grains become fuzzy. Moreover, we observe the accumulation of local plastic strains promoting the initiation of a system of cracks. By using the proposed original method based on the analysis of digital images, we estimate the direction of multiple cracking and show that the cracks propagate in mutually perpendicular planes.

We also evaluate the quantitative parameters of cracking of the roller at different depths under their outer surface. We propose a diagnostic interpretation of the analyzed parameters (in particular, the number of combined cracks and the direction of cracking are equal on the surface and in the subsurface layers down to a depth of 2 mm). The maximum crack lengths on the surface of a structure and in the subsurface layers are identical. As a result of oxidation of the surface, the number of identified cracks at depths of up to 2.5 mm becomes 1.5 times lower.

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