EVALUATION OF IN-SERVICE SURFACE CRACKING OF ROLLS OF CONTINUOUS CASTING MACHINES

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Abstract. The in-service damage in the material for rolls of continuous casting machines is investigated, in particular, the topology of surface cracks is studied, and their statistical analysis is made. Using the results of the microhardness measurements, the structural degradation of the material is evaluated depending on the distance to the roll surface.

Introduction

Cracking of the protective metal layer is an important degradation factor of bimetal rolls of continuous casting machines (CCM). The rolls operate in conditions of cyclic thermo-mechanical loading and high temperature.

The process of reconditioning and reuse of rolls removed from service that involves turning of a damaged layer and repair surfacing has received wide acceptance among enterprises and works [1-4].

Repair of rolls is made by the method of single-layer or multilayer surfacing with powder wire in order to produce the chromium metal with the chromium content of 13 to 18 % on their surfaces [1, 2, 4]. There also exist methods for resurfacing rolls without complete grinding of cracks, with the use of certain modes of thermal treatment only, which leads to their blunting [3].

However, the effective use of earlier mentioned design solutions is possible only with a thorough analysis of the geometry, mutual location of microcracks and their density on the roll surface, analysis of the metal damage at various depths of the roll [4].

The aim of this work is study of the in-service CCM roll material damage, in particular, the topology of surface cracks, their statistical analysis, the material hardness and microhardness.

Procedure for analyzing roll surfaces

The geometry of cracks was studied in a surface layer of a one-piece-forged roll from 25Kh1M1F steel manufactured at the "Illich Mariupol Metallurgical Combine" company. Heat treatment was as follows: annealing at a temperature of 920 ^{0}C, forging, anti-flaking annealing and normalizing at 950-980 ^{0}C with tempering at 650 ^{0}C. A final surface hardening is provided by quenching followed by tempering at 650 ^{0}C. After the above treatment, steel 25Kh1M1F has the following mechanical properties: σ_{YS} = 750 to 760 MPa, σ_{UTS} =850 to 870 MPa, δ =16.0...17.0 %, ψ =50.0...55.0 %, KCV =0.6...1.0 MJ/m^2, HRC =23...25 [5].

Cracking of the roll surface occurs as a result of the thermal fatigue caused by a regular contact with an annealed metal (1100-1200 ^{0}C) and cooling in a water steam atmosphere. The roll surface temperature varies from 450 to 670 ^{0}C in the contact zone and from 100 to 250 ^{0}C in the cooling zone.

The depth and layer-by-layer distribution of cracks were studied for the roll with the working portion diameter D=320 mm that was in service in a horizontal part of the CCM during 4500 melts without refacing, Fig. 1.

The dimensions of the surface cracks were determined on the polished end surfaces (A, B) and lateral ones (F, G) of the templates of length 220 mm, height $h_{max=}$ 40 mm and thickness b = 5 mm cut-out along the roller axis and in the radial direction (Fig.1).

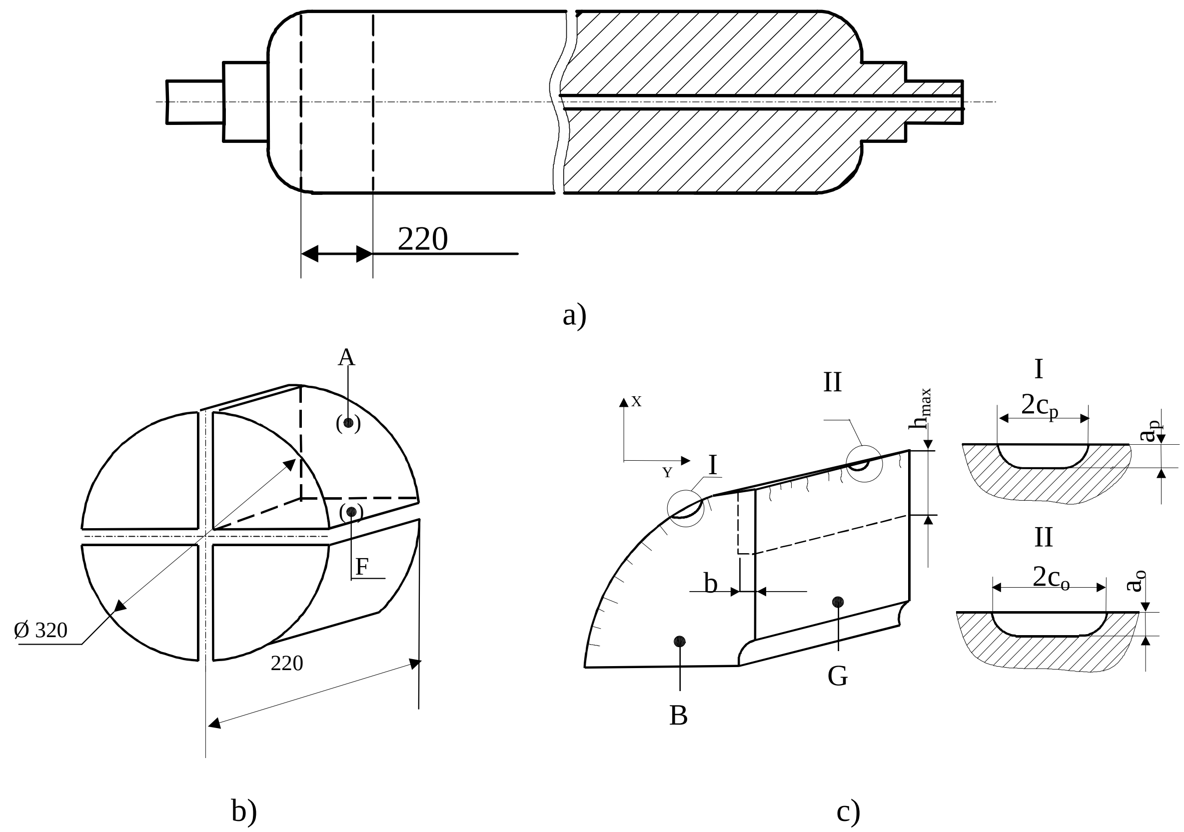

Fig. 1. Schematic of cutting-out the CCM roll segment of diameter 320 mm (a); cutting-out the template (b); the surfaces and cracks under study (c)

The following notation is used for the surface crack dimensions: a_p, a_o - the depth of the crack whose plane is perpendicular to the specimen axis and passes through the specimen axis, respectively; $2C_p, 2C_o$ - the length of the crack on the surface whose plane is perpendicular to the specimen axis and passes through the specimen axis, respectively. The template surfaces were studied using the type MBC-10 optical microscope at ×20-70 power. Using these templates, the variation in the hardness HRB and microhardness HV of the roll metal in the radial direction h_i was also studied.

Macroanalysis of the roll surface

With the use of the methods of macroanalysis of the template surfaces, the main circumferential cracks and network of cracks in rolls were detected on the roll surface (Fig. 2 a, b).

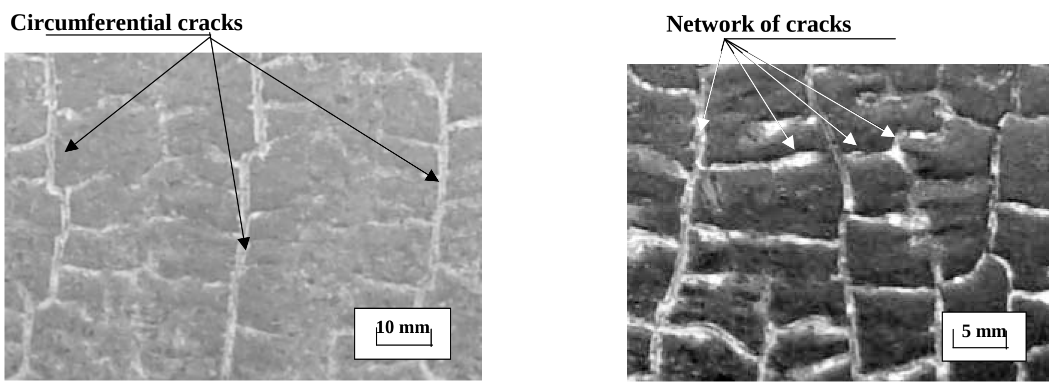

Fig. 2. Photographs of the surface of the CCM roll 320 mm in diameter with typical in-service damages after 4500 melts

The cracks in the plane that passes through the specimen axis have the shape of a half circle, which, in our opinion, is due to their location between the networks of radial cracks.

The relaxation of stresses was likely to occur at their edges, which slowed down their propagation along the roll axis.

The roll surface was coated by an oxide scale layer formed as a result of the action of high temperatures and contact with the slab billet (Fig. 2). It is known that a layer of the oxide scale no more than 0.09 mm in thickness is formed on steel in an air atmosphere after one thousand hours of operation at 600 ^{0}C [3].

Investigation of the geometrical parameters and mutual location of cracks

Since a CCM roll operates under conditions of high-temperature cyclic deformation, the cracking direction depends on the direction of the most intense strain defined by the formula

$$tan(2\theta_p) = \frac{\varepsilon_{xy}}{\varepsilon_x - \varepsilon_y},$$

where θ_p is the direction of the principal stresses; ε_x, ε_y are the strains in the direction of the axis *X* and *Y*; ε_{xy} is the shear strain.

The principal stresses on the roll surface that are caused by bending will be parallel and perpendicular to the roll axis, i.e., θ_p = 0 and 90^0. However, under the action of the thermal cyclic loading between the slab billet and roll, the direction of the principal stresses can change [6].

From this it follows that the most intense strain, exhaustion of the material plasticity and cracking on the roll surface will occur in the directions perpendicular and parallel to the roll axis.

The interrelation between the crack depth and length was studied in the planes that pass through the roll axis and in the planes that are perpendicular to it (Figs 2 and 3).

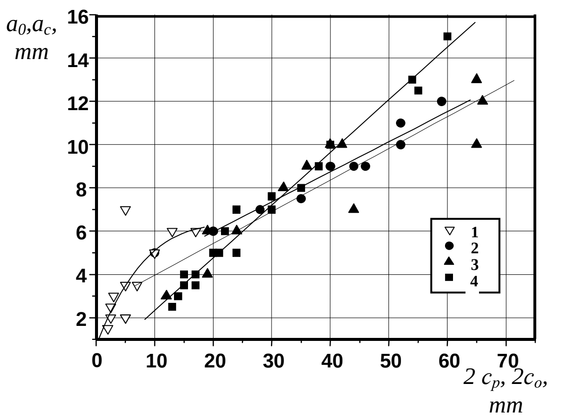

Fig. 3. Relationship between the crack depth and length on the surface in the axial plane (*1*) and in the plane perpendicular to the roll axis (*2*-*4*) (according to the data of works [1] (*2*) and [2] (*4*) and the cracks detected (*3*))

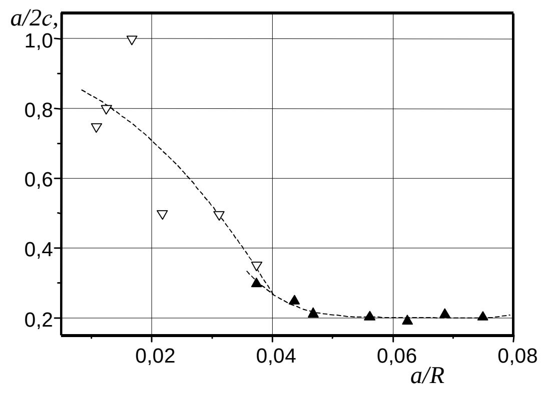

Fig. 4. Relationship between the crack shape factor and relative crack depth (See the notation in Fig.3)

The cracks detected in the plane perpendicular to the roll axis are deeper by a factor of 1.5 to 1.8 than the axial ones. The crack shape factor (the ratio of crack depth to crack length on a surface) decreases with the increase in the crack depth (Fig. 4). In particular, for cracks that lie in the axial plane, it decreases from $\frac{a_o}{2C_o}$ = 0.8 at the depth *a/R*= 0.01 to $\frac{a_o}{2C_o}$ = 0.35 at *a/R* = 0.36. The cracks that are in the plane perpendicular the specimen axis have the shape close to a semielliptical one, in particular, at $a/R = 0.037$, the crack shape factor $\frac{a_p}{2C_p} = 0.3$. Note that for $a/R \geq 0.05$, the shape factor for the cracks that are perpendicular to the specimen axis is constant and equal to 0.2 mm.

During visual examination of the roll, separate circumferential cracks were also detected. These were the coalescent elliptical cracks. Discontinuous radial cracks of a depth of $a_p = 8$ to 12 mm and the network of cracks were detected on the roll surface. The radial cracks are the breaks in the metal and are located normally to the roll surface at a step of 20-25 mm. The cause of their occurrence is the axial thermal stresses (in the direction of the longitudinal axis of the roll). The second largest stresses are the circumferential stresses resulting in the occurrence and growth of the axial cracks parallel to the roll generatrix, whose depths are lower than those of the radial ones by a factor of 2 to 2. 5.

Besides, a statistical analysis of the cracks of various depths was made. There were analyzed 153 cracks detected on 2 templates in the axial plane and 80 cracks in the plane perpendicular to the roll axis.

The specific distribution of cracks of different lengths in the radial and axial directions is given in Fig. 5. The cracks within the network of cracks constitute about 57% of the total number of the cracks under study. With their formation, the roll surface stresses decrease due to the increase of a free surface. However, they contribute to the intensification of the process of the corrosive oxidation and the subsequent wear of the working surface.

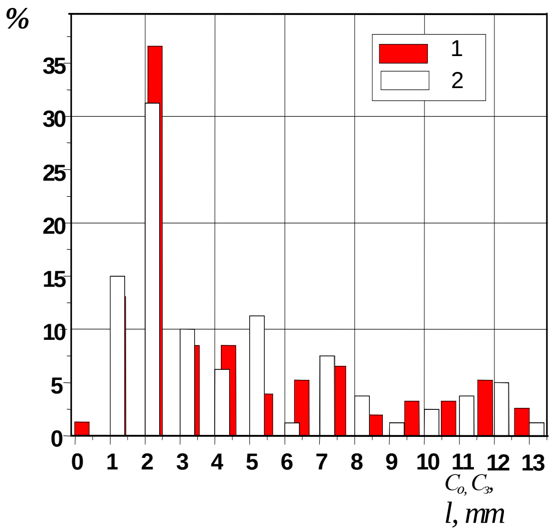

Fig. 5. Distribution diagram for cracks of different depths (%) detected on the template surface in the axial plane 1-F, G (*a*) and in the plane perpendicular to the roll axis 2-A, B (b) (See the notations in Fig. 1 b, c)

“Deep” cracks more than 10 mm in length constitute about 10% of the total number of the detected cracks. The depth of the longest crack among them is 13 mm. These cracks propagating in the roll body form a network of cracks which, by unloading the adjacent areas, creates the so-called “shadow zone” for the cracks of lower depths. This enables their adjacent areas to be expanded freely in heating and reduced in cooling.

However, on the other hand, such cracks are the most dangerous since these, propagating and merging, form circumferential cracks that can result in the complete failure of the roll.

Hardness and microhardness analysis by the roll depth

Hardness and microhardness were determined by the conventional procedure using both a Vickers hardness testing and PTM -3 hardness measuring instruments with a diamond-pyramid indenter, the angle of 136^0 at the apex, the indenter load of 0.3 H, the time of holding under load of 15 s in accordance with the performance requirements given in [8].

Hardness of steel 25Kh1M1F was determined at various distances from the outer surface of the roll. The hardness has been found to decrease with the distance from the outer surface. In particular, at a distance of 5 mm, the hardness was 92 HRB (192 HB), whereas at a distance of 38.5 mm, it was 85 HRB (166 HB). The obtained hardness values are somewhat lower than the reference value (269 down to 217 HB).

The structural nonuniformity of the material was described using the Weibull distribution [9]

$$P(\sigma) = 1 - e^{-\left(\frac{\sigma}{k}\right)^m}, \qquad (1)$$

where m, k are the parameters of spread with the parameter m (the homogeneity factor that reflects the degree of spread of the parameters of the quantity under study) being determined from the Gumbel formula

$$m = \frac{d(n)}{2{,}30259 \cdot S(lg\,HV)}, \qquad (2)$$

where $d(n)$ is the empirical value of the distribution function; $S(lg\,HV)$ is the standard deviation of the random quantity.

The quantities $d(n)$, $S(lg\,HV)$ were determined depending on the number of measurements, n = 22 to 25, according to the [8]. It is known that a lesser degree of damage conforms to higher values of the factor m.

The maximum microhardeness of 2500 MPa was found on the roll surface (Fig.6).

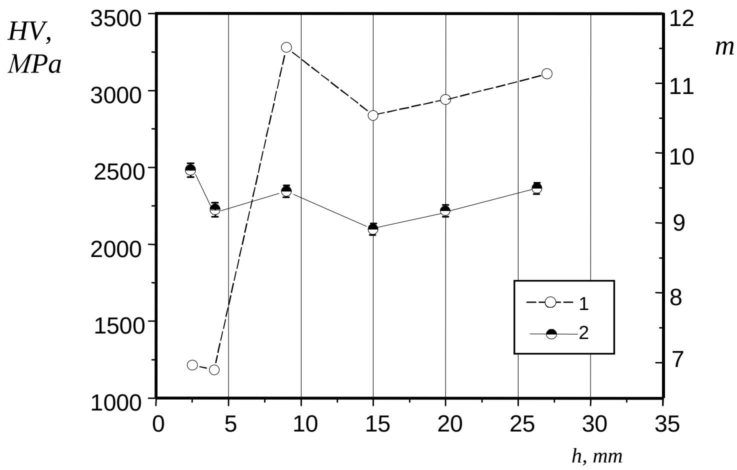

Fig. 6 Dependence of the homogeneity factor (1) and microhardness (2) on the distance in the plane perpendicular to the roll axis.

The microhardness decreases down to 2200…2350 MPa with increasing distance from the surface. A slight increase in the microhardness of the surface layers is likely to be caused by the process of the roll manufacture on the one hand, and the influence of operational conditions, in particular, the elastoplastic deformation of the surface layers and variation in the steel structure consisting in the pearlite decomposition, redistribution of carbides along the ferrite grains, on the other hand.

This is in agreement with the known data [9] when, under conditions of cyclic loading, only a slight change in hardness and microhardness is observed, and a weak correlation also exists between the given characteristics and structural state of the metal.

The use of the Weibull homogeneity factor makes it possible to detect the material degradation. In particular, a decrease in the value of the homogeneity factor to $m = 6.9$ indicates that the process of damage accumulation occurred considerably more intensively in the surface layers. At the final stage of heat treatment, tempering is likely not to result in the formation of the equilibrium structure, therefore in the process of thermal fatigue, the redistribution of the alloying elements and carbon in solid solution with dissolution of the existing carbide phases and precipitation of new ones is possible.

At a distance of $h = 9$ to 25 mm from the surface, $m = 9.5…11.5$, which is higher by 60 to 72 % than that in the near-surface zone, and this is indicative of the lower scatter in the microhardness and lower damage of the metal.

Conclusions

The topology of surface cracks has been studied in the one-piece-forged CCM roll of 25Kh1M1F steel removed from service after 4500 melts. A statistical analysis of the crack dimensions has been made, the specific weight of each of the groups of cracks has been determined in the plane that passes through the roll axis and in the plane that is perpendicular to the roll axis. The cracks in the plane perpendicular to the roll axis have been revealed to be deeper of 1.5 to 1.8 times than the axial ones.

It has been found that, independent of the crack plane orientation (axial or perpendicular to the roll axis), the crack shape factor (the ratio of crack depth to crack length on a surface) decreases with the increase in the crack depth.

Based on the microhardness measurements and statistical analysis, the material structural deterioration caused by in-service conditions has been evaluated depending on the distance to the roll surface. The damage degree in the surface layers of the roll material whose depths are in the range from 2.5 to 4 mm is higher by 60 to 72% than that at the depth $h = 9$ to 32 mm.

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