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DEGRADATION AND CYCLIC CRACK RESISTANCE OF CONTINUOUS CASTING MACHINE ROLL MATERIAL UNDER OPERATING TEMPERATURES*

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Abstract– The in-service cracks of the continuous casting machine roll are studied. The effects of high temperature fatigue crack growth were investigated for 25Kh1M1F steel, which is widely used for continuous casting rolls. In general, fatigue crack growth rates increased with increasing temperatures. At high crack growth rates, crack-tip plasticity was significant and propagation proceeded by ductile striation formation processes.

Keywords– Defects, fatigue crack growth, fractography, high temperature fatigue

1. INTRODUCTION

Rollers of continuous slab and casting machines (CCM) are exposed to significant static and cyclic loads during operation under conditions of thermomechanical loading [1-4]. Hard service conditions lead to the exhaustion of plasticity, degradation of the material strength properties and nucleation of crack-like defects [1]. Under the action of cyclic thermal and mechanical loading, the fatigue cracks grow and can achieve critical size leading to the roller's failure [5]. Fracture at high temperature has become a critical problem for CCM rollers [6]. Therefore, it is very important to approach such problems from the viewpoint of high temperature crack resistance [7].

There has been some recent work [1-3, 5-8] using fracture mechanics approaches to determine the extent of high temperatures on the fatigue crack resistance. The general conclusion from these studies is that depending upon the material and the temperature of the test, crack growth rates increase during cyclic loading.

Since fatigue crack resistance and high temperatures are closely related to such component failures, the fatigue durability of high temperature components must be evaluated through fatigue crack growth tests, and based on these results, better operating conditions can be determined [8]. At the same time, considering the effects of temperature on the cyclic crack resistance of the material and investigation of the crack growth mechanisms under operating temperatures applied to structures remain topics in engineering problems [1, 9].

In this paper, the characteristic mechanisms of the in-service damageability of the roller surface and the effect of operating temperatures on the macro- and micro-regularities in fatigue crack resistance of heat resistant steel 25Kh1M1F, traditionally used for the production of CCM rollers, is investigated.

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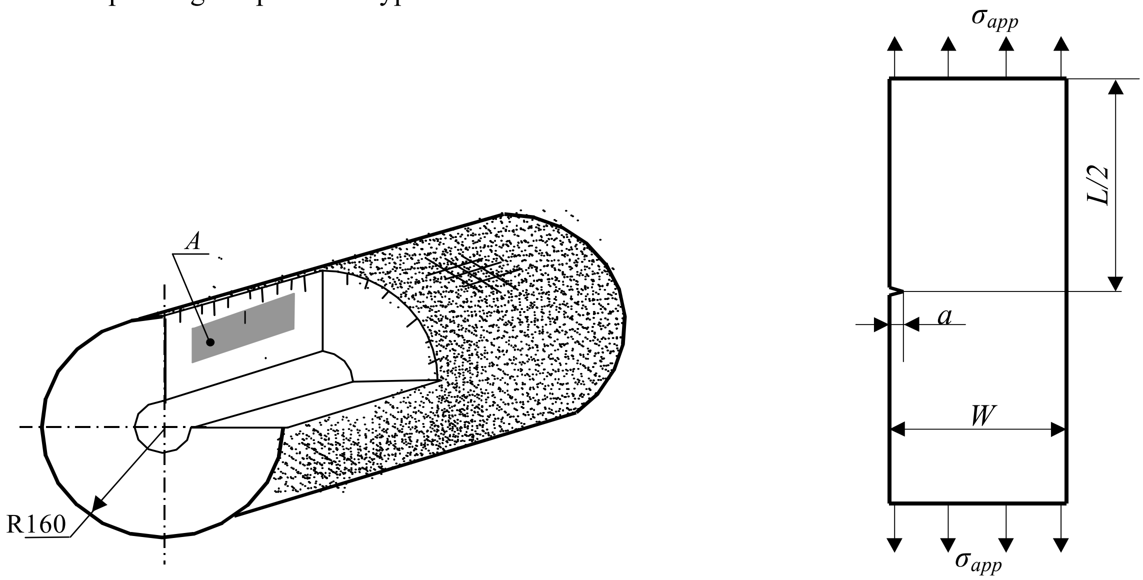
2. RESEARCH TECHNIQUE

The in-service surface damage of the roller with diameter is 320 mm from steel 25Kh1M1F after 4500 melts was investigated at the Ilyich Iron and Steel Works of Mariupol (Ukraine) Fig. 1a. The parameters of the network of thermomechanical fatigue cracks were analysed. Since during a significant part of its service life the roller is operated with crack-like defects, the development of which often determines the life of the structure, the investigations of the cyclic crack resistance of laboratory specimens were carried out under the operating temperatures typical for the roller.



(a) (b)

Fig. 1. Cutting scheme of specimens (A) – a and single-edge-notch tensile specimen (SENT) - b

The cyclic crack resistance tests were performed on the CTM-100 servo-hydraulic test machine with the loading frequency of 1.0 Hz. The fatigue crack growth rate (FCG rate) was determined under the uniaxial tensioning of plates with lateral notches at temperatures of 20, 375 and 600 °C and the cycle asymmetry coefficient $R = K_{min}/K_{max}=0$. Here, K_{min} and K_{max} are the smallest and the largest stress intensity factors (SIF) of the cycle, respectively.

The crack growth rate was described by the Paris equation:

$$\frac{da}{dN} = CK_{\max}^{m} \quad (1)$$

where C and m are the material constants;

The stress intensity factor (SIF) of single-edge-notch tension specimen was determined from formula [8, 10]:

$$K = \sigma_{app}\sqrt{W} \cdot F_1\left(\frac{a}{W}\right) \quad (2)$$

for $L/W = 4$:

$$F_1\left(\frac{a}{W}\right) = 0{,}288 + 3{,}779\left(\frac{a}{W}\right) - 1{,}985\left(\frac{a}{W}\right)^2 + 3{,}662\left(\frac{a}{W}\right)^3$$

where a is the crack length; N is the number of loading cycles; σ_{app} - applied tensile stress.

Micromechanisms of the FCG rate in the CCM roller material were investigated using the REM-106I scanning electron microscope.

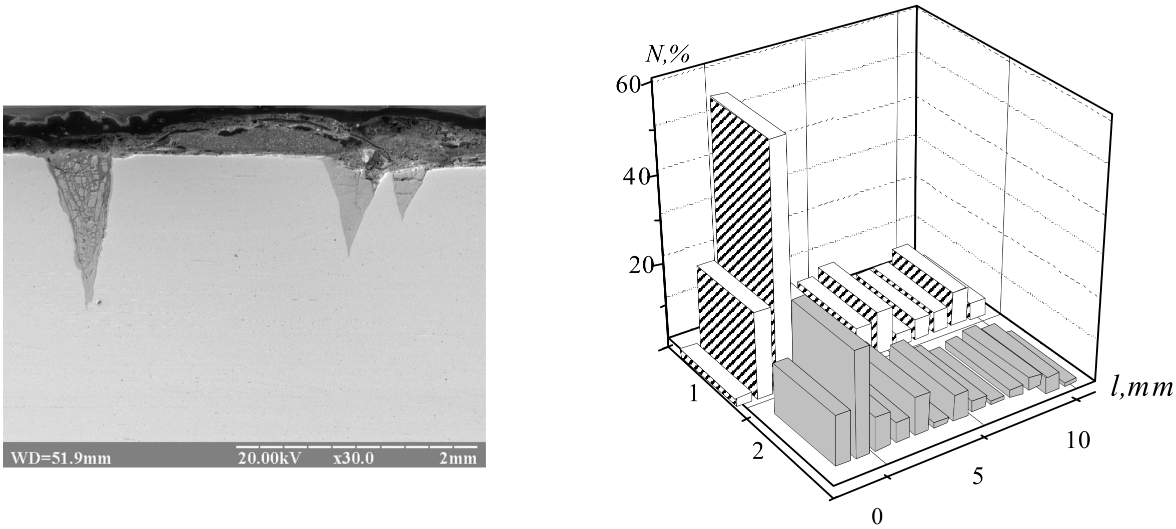
3. RESULTS AND DISCUSSION

a) Macroanalysis of the CCM roller surface

It is known that the roller surface is operated under the cyclic variation of temperature within the range of $375 \leftrightarrow 600$ ^{o}C, and the internal layers of the CCM roller operate under conditions of quasistationary loading, whereas near the cooling outlet the temperature does not exceed T =60^{o}C [1-4].

The crack geometry was analysed in the axial and radial directions on the reference length of 400 mm (Fig. 2a). The depth of radial cracks was 8 ... 12 mm. Moreover, they are 1.5 ... 1.8 times deeper than axial cracks. The crazing is practically the same in both directions investigated, its depth is from 1 to 5 mm.

Based on the statistical analysis of the detected cracks it is established that all the available defects can be conventionally divided into two groups: cracks with length up to 2.5 mm – a "crazing", which makes up to 60 % of all defects, and a network of "deep cracks" with depths > 2.5 mm [11, 12]. The specific distribution of cracks in the radial and axial directions is shown in Fig. 2b.



(a) (b)

Fig. 2. Photo of the surface layer of the CCM roller with a crazing due to service exposure – a; and distribution of the depth lengths of fatigue cracks in the axial (1) and radial (2) planes – b

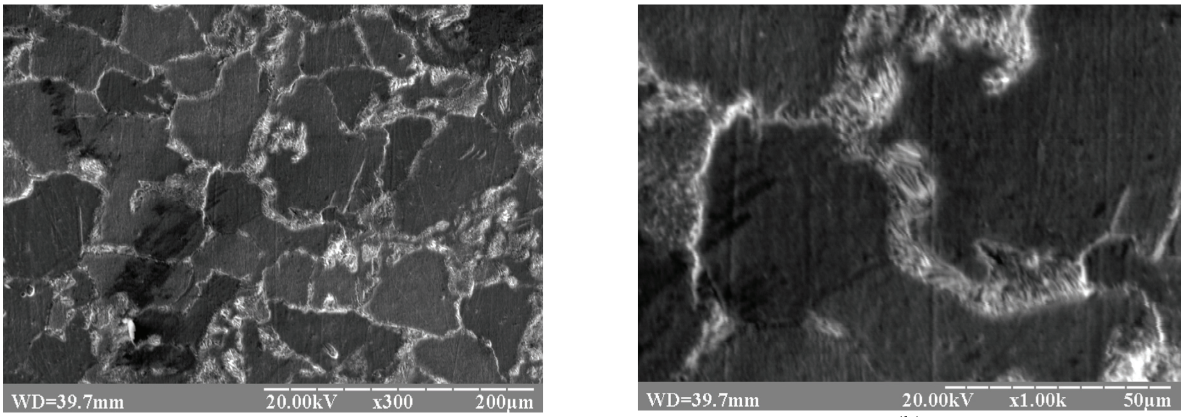
"Deep" cracks with lengths exceeding 10 mm make up approximately 10% of the general amount of cracks detected. In addition, long cracks play a dual role: on the one hand, they create a "shadow zone", thus leading to the arrest of nearby defects, and, on the other hand, their propagation may lead to an unpredictable failure of the roller [1].

b) Cyclic crack resistance of the CCM roller material

The roller material is steel 25Kh1M1F, which belongs to the ferritic-pearlitic class. Nominal alloy composition is C-0.25; Cr-1.0; Mo – 1.0; and V - less than 1.0 in weight percent [1].

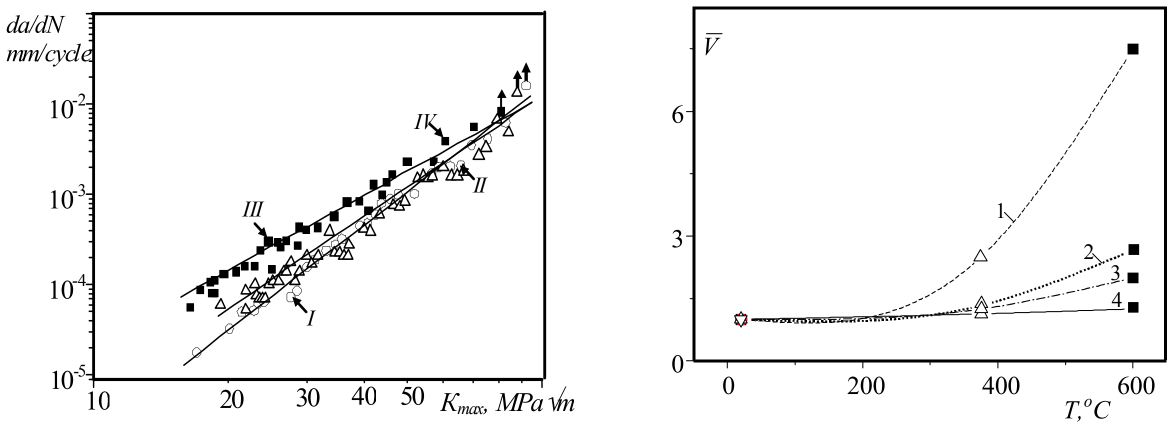
It contains pearlite grains approximately 30...50 μm in size that are distributed within the ferritic matrix (Fig. 3a). The islands of pearlite grains can be clearly seen within the ferritic matrix (Fig. 3b).

The ferritic-pearlitic structure of the steel, which is characterised by high strength, ensures its compliance with the requirements regarding the plasticity and strength in high temperature conditions. It should be noted that for all the temperatures considered the regularities in fatigue failure of steel 25Kh1M1F have a "classical view". In addition, the slope of the diagram describes the intensity of damage accumulation. The results of the investigation into the fatigue crack growth rate (FCG rate) in coordinates da/dN- K_{max} at room (20 ^oC), elevated (375 ^oC) and high (600 ^oC) temperatures are given in Fig. 4a, arrows indicate the points of fractographic microanalysis.



(a) (b)

Fig. 3. Structure of steel 25Kh1M1F in the initial state – a; one island of pearlite grains - b



(a) (b)

Fig. 4. Dependence of fatigue crack growth rate on temperature in absolute – (a) and relative – (b) coordinates; I, II, III, IV – points of fractographic analysis; 1,2,3,4 – the FCG rate at K_{max} = 20, 40, 50, 80 $MPa\sqrt{m}$, respectively

It is found that within the range of $18.0 \leq K_{max} \leq 20.0$ $MPa\sqrt{m}$ the FCG rate at 375 ^oC is 3 times higher, and at 600 ^oC it is 8 times higher than at 20 ^oC. With an increase in the crack length and the maximum SIF value, the difference between the FCG rates at normal and elevated temperatures will decrease. At $K_{max} \geq 80$ $MPa\sqrt{m}$, the FCR rate for all the temperatures considered is the same and makes 8.0 10^{-3} mm / cycle (Table 1).

Table 1. Material constants of 25Kh1M1F steel

Type of steel	Temperature, ^0C	Parameters of the Paris equation (2)	
		C, $\frac{mm/cycle}{\left(MPa\sqrt{m}\right)}$	m
25Kh1M1F	20	$5.51\cdot10^{-10}$	3.60
	375	$7.40\cdot10^{-10}$	3.56
	600	$1.32\cdot10^{-8}$	3.01

The sensitivity of the FCR rate to the temperature effect was evaluated by coefficient:

$$\overline{V} = V_t / V_{20},$$

where V_t is the FCG rate for elevated (375 °C) and high (600 °C) temperatures. All the results presented correspond to the middle section of the kinetic diagram of fatigue failure. In our opinion, it is necessary to distinguish several reasons for the reduced crack resistance of steel 25Kh1M1F with an increase in temperature: a decrease in the material strength due to the activation of dislocation processes; an increase in the scale level of deformation, which leads to the intensified damage accumulation as compared to that during tests at 20 °C; an increase in the damage accumulation kinetics.

At 20 °C (in point I), the formations of fatigue striations located on the facets of the fatigue fracture surface were detected (Fig. 5a, b). The availability of sliding planes that intersect secondary cracks is typical of the middle section of the diagram. The width of fatigue striations is somewhat different in various points of the crack front. This is preconditioned by the non-uniformity of the crack front growth.

With an increase in K_{max} (p. II) the effect of inclusions and dispersed particles on the mechanisms of fatigue crack propagation becomes more pronounced. On the failure surface, large separation pits formed during the separation of inclusions from the matrix can be seen, as well as individual cracked inclusions. Considerable deformations along the body and boundaries of grains assist in the development of the plastic zone at the crack tip, leading to the intensification of failure processes, and causing the formation of individual microcracks, which then coalesce with the main crack. The traces of such coalescence create notches on the fracture surface [13].

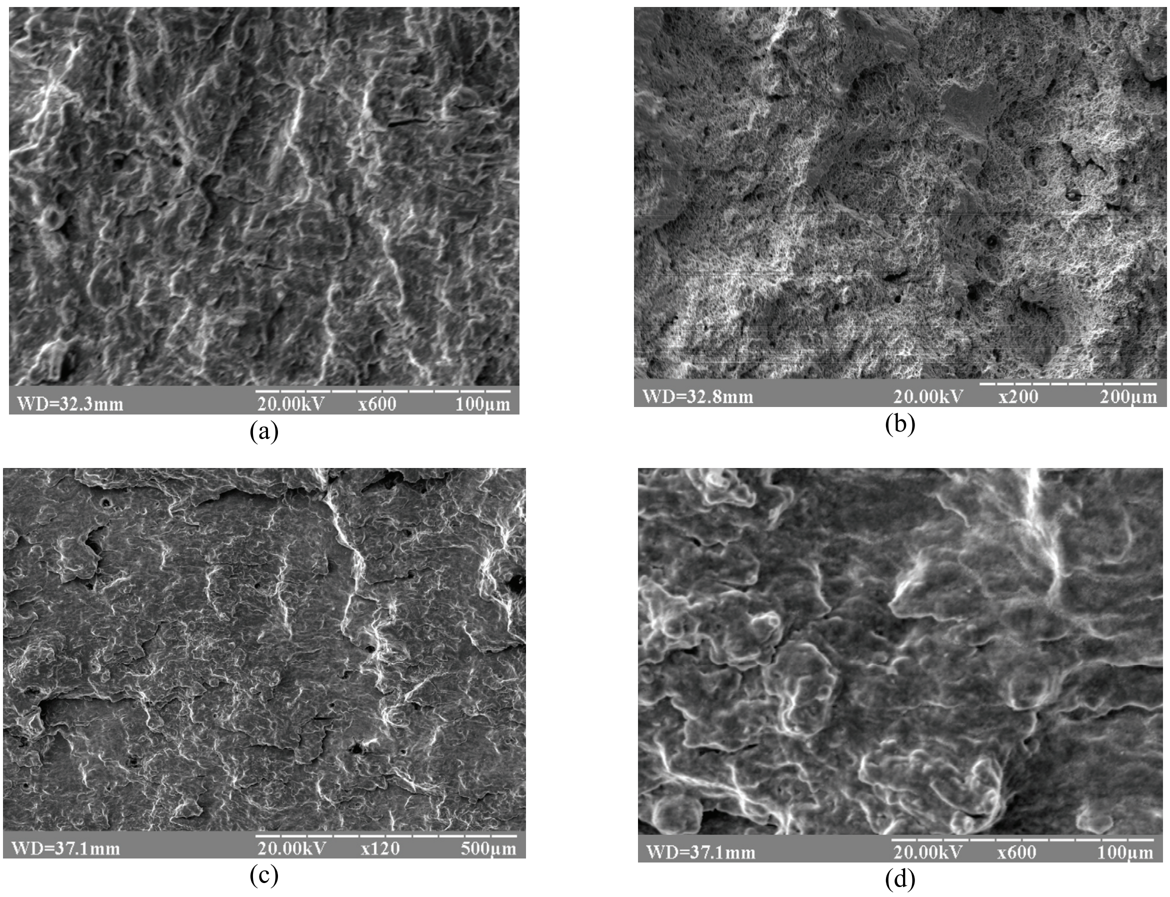


Fig. 5. Micromechanisms of fatigue crack propagation in steel 25Kh1M1F at 20°C (a, b) and 600 °C (c, d) in points I, II, III, IV, see Fig. 4

At 375 ^{o}C, the mechanism of failure differs from the one described above in a certain respect, because it is first of all accompanied by the intensive intergranular plastic deformation. A high non-uniformity of deformation of structural elements should be noted as well. Moreover, such peculiarities of failure as secondary cracks, sections of intergranular failure with a large amount of folds, and the formation of microcracks on the grain boundaries were found.

At 600 ^{o}C, diagonal facets and some fatigue striations were found only in p. III. In the rest of the sections of failure, in particular in p. IV, the accumulation of small dimples with a diameter of about 0.4 μm and individual large separation dimples with a diameter from 2 to 4 μm were observed. Except for the local sections that adjoin the lateral sides of the specimen, the macrocrack was propagated by the ductile mechanism. The dispersion of sizes of the main elements of fracture microrelief (dimples) testifies to the local non-uniformity of the fatigue fracture process in the material studied [14].

Therefore, under conditions of the elastic-plastic failure, quite energy-intensive mechanisms of FCG were found both at 20 ^{o}C and at 600 ^{o}C. Besides, the view of the failure surface depends on the degree of localisation of plastic deformation.

This work is devoted mainly to the experimental investigation of the fatigue crack resistance of the steel 25Kh1M1F. The next stage of research in this area will be building a model of continuous casting machine roller with a crack using finite element method [15]. This allows the stress-strain state of the structure to be calculated and results obtained in this paper to be used to predict the durability of the roller.

4. CONCLUSION

The effect of operating temperatures on the crack resistance of steel 25Kh1M1F is investigated in this paper. In general, 25Kh1M1F steel showed an increase in crack growth rate at high temperature conditions. It was found that within the range of $18.0 \le K_{max} \le 20.0$ $MPa\sqrt{m}$ the FCG rate at 375 ^{o}C is 3 times higher, and at 600 ^{o}C it is 8 times higher than at 20 ^{o}C. At $K_{max} \ge 80$ $MPa\sqrt{m}$, the FCR rate for all the temperatures considered is the same and makes 8.0 10^{-3} mm / cycle. The equations describing the regularities in the crack growth are presented.

Based on the analysis and interpretation of the fracture pictures, the relationship between the micro- and macromechanisms of the fatigue crack growth is shown. The dominant mechanism of fatigue crack growth in all specimens was the intergranular type fracture, but at 600 ^{o}C the individual large dimples with diameter from 2 to 4 μm were found at the interface between coarse carbide and grain boundary.

The results obtained are the basis for the prediction of the effect of high and elevated temperatures on the residual life of the CCM roller after determining the parameters of crack-like defects by the non-destructive control methods.

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