ISSN 1392 - 1207. MECHANIKA. 2011. 17(3): 251-254

Diagnostics of thermal fatigue cracks on continuous caster rolls surface

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crossref http://dx.doi.org/10.5755/j01.mech.17.3.499

1. Introduction

Efficient and smooth production of slabs depends on the condition of technological equipment, in particular, continuous billet casting machines (CCM) [1]. CCM rolls are operated under thermomechanical loading, which causes multiple cracking of the working surface.

This paper describes the analysis and identification of continuous caster roll (CC) surfaces damage and cracking by means of nondestructive testing methods and digital photography.

Estimating damage and the remaining life of CCM rolls or high-temperature fatigue condition has become relatively common. Information on thermal fatigue damage effects in operational condition is urgently needed for design purposes [1].

There is experience of nondestructive testing (NDT) of the hardness and depth of the active hardened layer roll made from steel 25Kh1M1F. Nominal alloy composition is C-0.25; Cr-1,0; Mo – 1,0; and V - less than 1,0 in weight percent [1].

Quality inspection of steel with the use physical methods is widespread as an inspection of the mechanical properties of continuous casting machines rolls [2]. As an alternative assessment method of a technical diagnostics is to use hardness measurements that can be correlated with thermal fatigue damage [1, 3].

An automated analysis of digital images showing segments of the inspected surface has a good potential for technical diagnosis of CCM rolls' condition [4, 5]. The existing methods for studying surface cracking usually consider a flat image (2D), which does not represent the true physical nature of the cracked surface and imposes certain limitations on diagnosis.

The crack geometry can be reproduced with greater accuracy by reconstructing a 2D image of the surface defect into a 3D one. Only a few works dealing with this problem are known, in which the basic principles of reconstruction are given. However, they all need to be improved further and customized to every particular type of cracking observed on the object analyzed [5].

In this paper, physical regularities of the CCM roll surface cracking are investigated, and an approach to the reconstruction of the crack depth based on the analysis of its 2D image is proposed.

2. Experimental procedures

Rolls being in service in a horizontal part of the CCM during 4500 melts without refacing were examined. The working portion diameter of the rolls was equal to 320 mm.

The object of the digital analysis was a standard surface segment of the CCM roll with a network of cracks, Fig. 1.

Hardness was measured with the Super Rockwell 200HR-150 hardness tester with the indentation load of 150 N; the coercive force was measured with the KRM-C-K2M device. Specimens were prepared from CCM roll after 4500 melts.

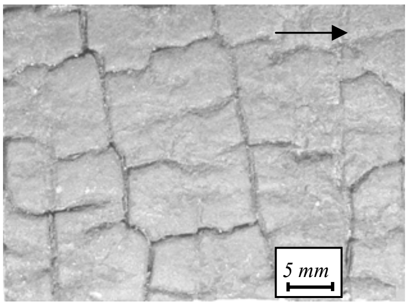


Fig. 1 Segment of the cracked surface with sections of cracking formed under various coalescence conditions

The network of cracks was photographed and subjected to the automated analysis. The result of the above operations was a geometrical model of the surface, in which coordinates of all characteristic points (nodes, fractures, branching) of the cracked structure are given. A numerical analysis of slope angles and segments lengths of the cracked structure is performed [3].

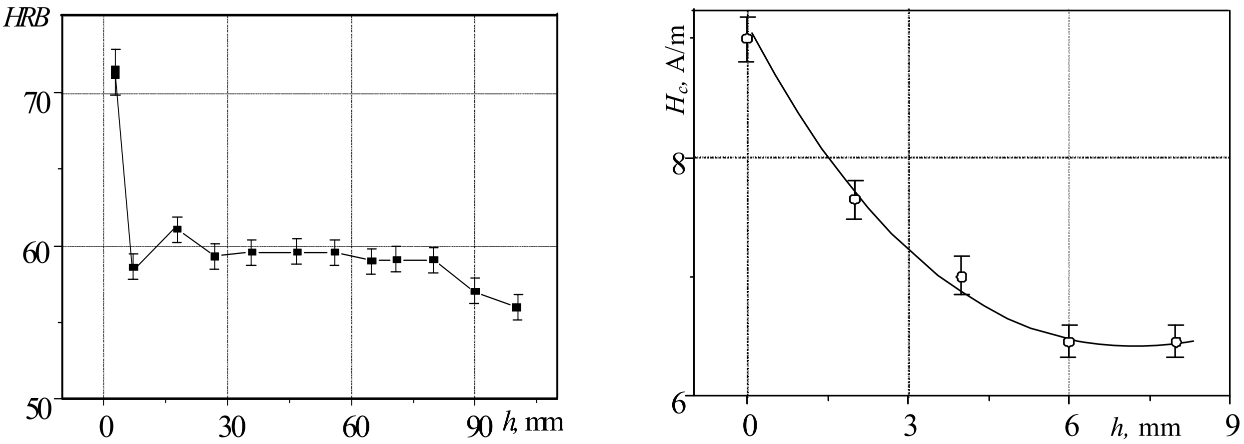
3. Result and discussion

Variation in microstructure and hardness of roll were studied using coercive force and hardness measurement technique. Fig. 2 shows hardness and coercive force as a function of depth from surface of the roll. There was some scatter in hardness measurements from indent to indent, mainly due to the nonuniform structure with varying dislocation density in the ferrite and perlite grains of 25Kh1M1F steel.

After thermocyclic loading, irreversible changes were observed in the properties and structure of the metal of the CCM roll surface layer. It should be noted that the hardness and coercive force value decreases monotonously with an increase depth from surface of the roll *h*, Fig. 2, a, b.

The in-service phenomena include the structural physical degradation of the material (Fig. 2), loss of plasticity, accumulation of dispersed microdefects whose merge in the most heavily stressed zones causes the formation of cracking [1, 4].

It is known that the growth of individual cracks within the network may lead to the coalescence of cracks, the result of which is a reduced number of cracks with a greater length, Fig. 3.



a

b

Fig. 2 a - change of hardness; b - coercive force on the surface depth (direction of scanning is show by the arrow Fig. 1)

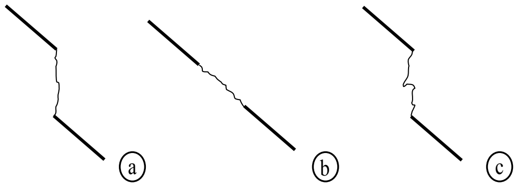


Fig. 3 Schematic representation of crack coalescence conditions: *a* – tension, *b* – shift, *c* – shift and tension

An integral direction of cracks propagation within the multiple cracking network was determined, Fig. 4. The overwhelming majority of cracks are oriented in orthogonal directions at angles of 90° and 180°, respectively [4].

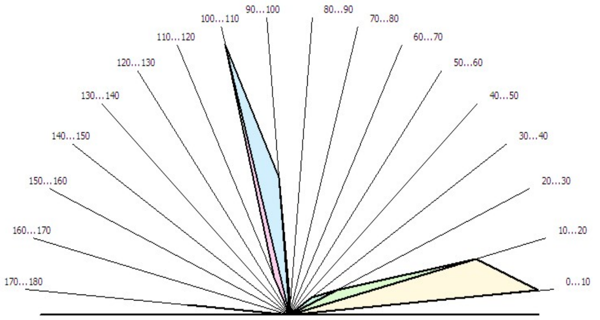


Fig. 4 Direction of cracking on the analyzed surface

This proves that the cracks coalesced under combined action of compressive and tensile stresses.

This agrees well with the provisions of the maximum tangential stress theory, which links the tensile and compressive stress intensity factors to the direction of crack propagation θ [6].

$$\theta = \mp cos^{-1}\left(\frac{3K_{II}^2 + K_I\sqrt{8K_{II}^2 + K_I^2}}{9K_{II}^2 + K_I^2}\right)$$

where K_I, K_{II} are the tensile and compressive stress intensity factors, respectively.

This equation substantiates the physical need in measuring the angle of cracks orientation and shows the relationship between this parameter and the criterion of the stressed-strained material. It also demonstrates the relation of this work to the classical works on fracture mechanics [6]. It is clearly seen from the equation that a change in the crack orientation angle will influence the stress-strain state of the material.

Based on the visual examination of the roll surface and the automated analysis of digital images, it was found that the cracks located along the roll axis are, as a rule, from 1.2 to 1.5 times shorter. The defects perpendicular to the roll axis merge with the former into a network of “coalesced cracks”.

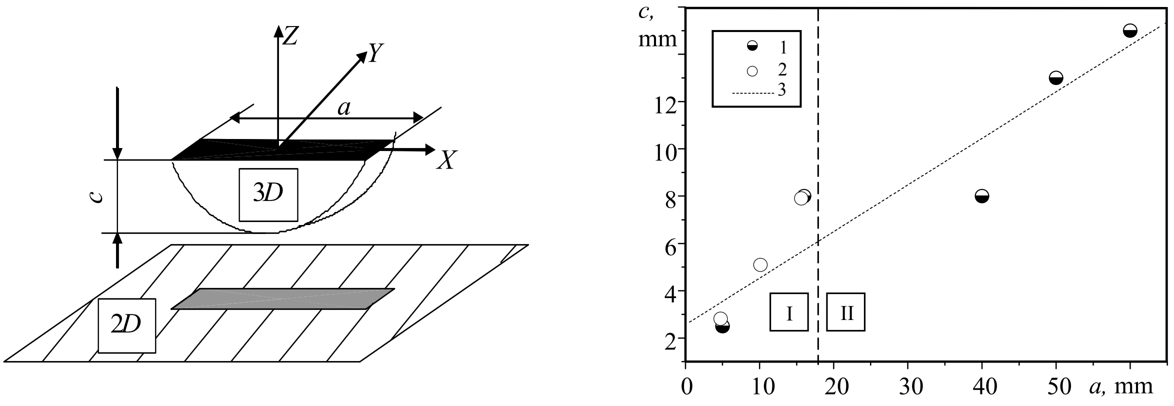
In order to reveal the geometrical parameters of cracks within the network, layer-by-layer grinding of the cracked surface was performed, followed by the analysis of the resulting crack lengths. This allowed obtaining the relationship parameters between the crack depth and length in the axial plane and in the direction perpendicular to the roll axis, Fig. 5, a.

While generalising the results obtained, two sections can be distinguished in the diagram, which describe the regularities in the crack shape change, Fig. 5, b. For cracks $a < 18$ mm (section I) a strong influence of multiple defects is noticeable, due to which the defect acquires the semicircular shape. During further crack growth within the range $18<a<60$ mm (section II) the shape of the crack becomes semi-elliptical. The results obtained are confirmed by the results of the analysis on fractures of CCM rollers.

For the investigated set of images, the ratio between axes was $c/a = 0.52 \pm 0.04$. According to the data obtained, this ratio can be approximated by linear equation, which allows determining the crack depth from the parameters of the identified crack lengths, Fig. 5, b. It should be noted that the ratios between the geometrical parameters of the surface cracks obtained in our experiment are in a good agreement with our previous results [5].

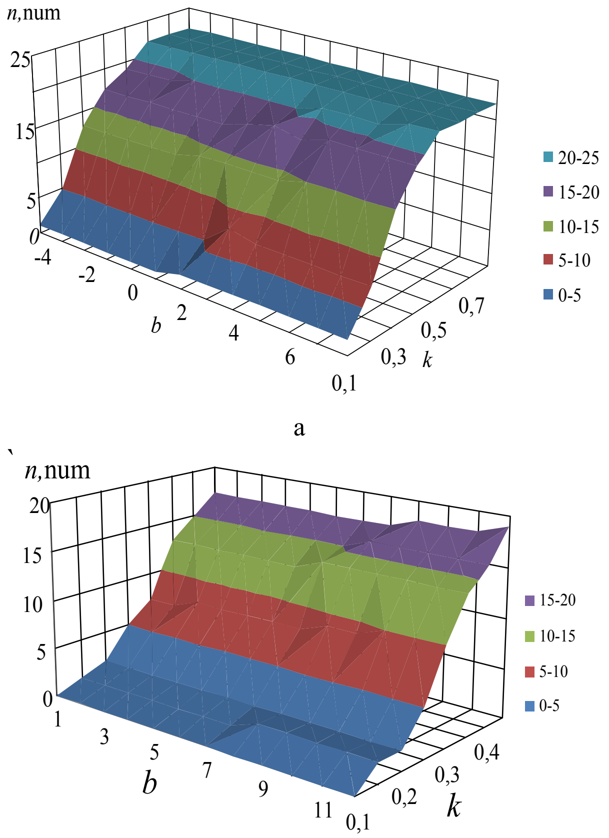
In addition, the adequacy of the parameters identification for the cracked structures in the surface and near surface layers was checked.

Based on the established relationship between the crack depth and length, i.e. $a = kc + b$ (where *a* is the crack depth; *c* is the crack length), the interpolation coefficients *k* and *b* were found, at which the calculation error is minimal.



a b

Fig. 5 a - 2D and 3D images of cracks; b - dependence between the crack length and depth



a

b

Fig. 6 Dependence of the regression equation parameters on the crack depth: a - for a surface crack; b - after grinding 3 mm off

The graphs of the detected cracks distribution are obtained along with the coefficients of the regression equation that describes the shape of the crack identified, Fig. 6.

Based on the analysis of the cracked surface structures, a reduced number of cracks was revealed after the removal of 3 mm thick layer of the material. The shape coefficients of the cracks identified varied within the range $c/a = 0.50 \ldots 0.55$.

Approaches are developed, which allow determining the depth of cracking (3D) from the parameters of a two-dimensional defect (2D) taking into account the preliminarily revealed geometric peculiarities of the cracked structure formation [1, 4, 5].

A well known approach is employed, which consists in using the a priori information about the structure of the relevant surface segment. The following reconstruction procedure is proposed:

- crack contours are outlined on 2D images, their dimensions and slope angles relative to the horizontal line are calculated;
- the depth and shape of the crack are reconstructed from the length parameters;
- programmed and physical cuts are made on the obtained model of the cracked structure, and the resulting geometrical cracking structures are compared;
- the shape coefficient is corrected taking into account physical regularities of cracking;
- the obtained 3D-model is visualized.

By the “programmed cut” a change of the cracked surface parameters in horizontal direction was meant, due to which an image was obtained at a certain depth, Fig. 7.

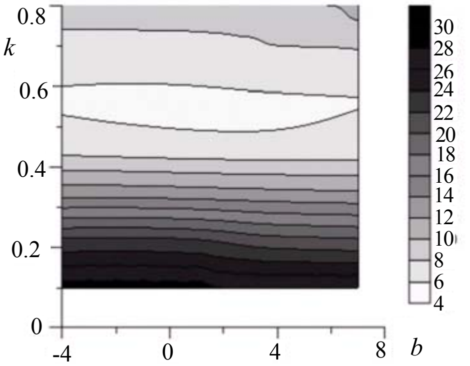


Fig. 7 Dependence of the calculation error in determining crack parameters on the interpolation coefficients

This allowed checking the adequacy of the algorithm operation and getting additional information about the cracked structure and physical regularities of its formation [6-8]. This method allows performing the analysis of crack shape changes after machining, which is relevant for the rolls with an organized network of cracks.

3D reconstruction of the network of cracks allows revealing the geometry of their cross-sections in various projections, determine a dominant mechanism of crack propagation and peculiarities of the stress-strain state of the inspected surface segment.

4. Conclusions

Physical regularities of defects coalescence on the surface of CCM rolls are analyzed. It is found that an increased surface cracking is caused by two factors, i.e. the growth of the existing cracks and the initiation of new ones.

3D reconstruction of the crack shape based on the geometry analysis of surface defects of CCM rolls is proposed. By means of reconstruction, crack depths distribution is obtained. The developed approach was realized as a stand-alone program module for the automated analysis performed on structures with multiple cracking.

The developed method can be used for the express-diagnosis of technical condition of the elements of metallurgical equipment condition and their residual life assessment.

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ŠILUMINIŲ PLYŠIŲ TOLYDINIO LIEJIMO MAŠINOS RITINĖLIO PAVIRŠIUJE DIAGNOSTIKA

Reziumė

Ištirtas magnetinio metodo taikymas nuovargio pažeidimų tolydinio liejimo mašinos ritinėlio paviršiuje kontrolei. Atlikta tolydinio liejimo mašinos ritinėlio paviršiaus įtrūkimų analizė ir identifikavimas pagal skaitmeninį vaizdą. Išnagrinėta trimatės pažeisto paviršiaus vaizdo rekonstrukcijos pagal plokščią vaizdą problema. Remiantis nustatytais fiziniais įtrūkimų dėsningumais pasiūlyta plyšio fronto rekonstrukcijos sistemos struktūra. Pateikti teoriniai ir eksperimentiniai rezultatai.

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DIAGNOSTICS OF THERMAL FATIGUE CRACKS ON CONTINUOUS CASTER ROLLS SURFACE

Summary

Application of magnetic method of control allows effectively estimating the fatigue damage accumulation in the working layer of CCM roll. The effects of the thermal fatigue cracking and operational damage process on the coercive force and hardness have been studied. It is shown that damage of steel 25Kh1M1F appreciably affect the coercive force and hardness in surface layer of the roll.

This paper also describes the analysis and identification of continuous caster (CCM) roll surfaces cracking by means of a digital photography. The problem of three-dimensional (3D) models cracks reconstruction in at a cracked surface of input 2D data is reviewed. Theoretical aspects and experimental results are presented.

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Р.Т. Бищак

ДИАГНОСТИКА ТЕРМОУСТАЛОСТНЫХ ТРЕЩИН НА ПОВЕРХНОСТИ РОЛИКА МАШИНЫ НЕПРЕРЫВНОГО ЛИТЬСЯ ЗАГОТОВОК

Резюме

Рассмотрено использование магнитного метода для контроля накопления усталостных повреждений в рабочем слое ролика МНЛЗ. Проведен анализ и идентификация элементов поверхностного растрескивания ролика МНЛЗ на основании анализа цифрового изображения его рабочей поверхности.

Рассмотрена проблема трехмерной реконструкции (3D) поврежденной поверхности по плоскому (2D) изображению. Представлены теоретическое описание и экспериментальные результаты.

Received January 12, 2011
Accepted June 15, 2011