Investigation into the geometrical parameters of a thermal fatigue crack pattern

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Abstract: A procedure for numerical analysis of the surface state of a roll for a billet continuous casting machine at the stage of coalescence of thermal fatigue cracks has been developed and implemented which is based on the identification of photo image elements. The scientific background and formal methods for optical inspection quality control are proposed on the basis of the optimization of the system input parameters.

Key-Words: - thermal fatigue, crack pattern, continuous casting machine, roll, damage

1 Introduction

Existing methods for calculating the residual life of rolls for billet continuous casting machines (BCCM) are based on the fracture mechanics principles. However, these procedures for predicting the residual life are not sufficiently reliable, which leads to considerable errors [1,2]. One of the causes for the overestimation of the design service life of a structure is little understanding of the process of coalescence of surface cracks, which makes it impossible to assess the degree of damage to a roll in full and to ensure the operating safety [3,4].

The main way of obtaining the information on a roll state is its technical diagnostics based on the nondestructive inspection techniques. The optical inspection of surface damage, and the assessment of the microcrack morphology in particular, is very promising [5, 6]. In order to create hardware/software tools for diagnostics of an object state, it is necessary to validate physical models, software and adequacy of identification and measurement of the damage accumulation processes [6].

The aim of the present paper is to develop the conceptual framework and scientific-methodical support for the quality control of optical inspection of surface crack network for enhancing the safety of critical-purpose elements (using a roll for BCCM as an example).

2 Procedure for roll surface analysis

We propose a method for assessing the surface damage to a BCCM roll based on processing of photo images of the surface under study. To solve the posed problem, the software has been developed that makes it possible to carry out technical diagnostics of BCCM roll state based on photo images of roll fragments. The software makes the analysis of the input images and calculates the geometrical characteristics of straight fragments of cracks, crack area and number of coalesced cracks within a preset accuracy. The calculation results are displayed in the form of histograms and in numerical form.

This software, while simplifying the assessment of the state of a photo image, is mainly focused on the mathematical processing of the results obtained. By making a regular analysis of the state of the roll test areas, it allows the kinetics of the damage accumulation to be revealed [7].

The algorithm of the software for analyzing photo images operates in the following manner. First, a binary conversion is performed for an input color image as a result of which the binary image \( \beta \) is produced (Fig. 1, a). This measure makes it possible to reduce the amount of information to be processed and to accelerate the process of searching for cracks in the image. A binary conversion is an important preparatory stage for the operation of the image recognition algorithm, since it is the image \( \beta \) that provides the output data to be analyzed for the presence of cracks.

The image \( \beta \) contains a great number of small separate subimages that make the analysis process more difficult. Therefore, a binary image is filtered using a linear balanced filter with a square kernel. It is also possible to use a filter with a kernel in the form of the Gaussian distribution, however, as it has been found experimentally, no improvements in the algorithm operation are observed in this case, whereas the computation time increases. Then the obtained multigrade image \( \Phi \) is binarized by comparing it with a certain boundary value of the background, as a result of which the image \( \Psi \) is
formed that describes a general picture of cracks and their borders (Fig. 1 (b)). Since the physical nature of thermal fatigue cracks on the surfaces under analysis is the same, it is possible to select such value of the background boundary, at which the above transformation allows one to reveal crack borders in the resulting image to a high degree of validity.

After this, a segmentation of the image \( \Psi \) is performed that makes it possible to divide the image into its constituent subimages and thus to reveal the areas belonging to the appropriate cracks. At this stage, it is possible to compute the total area of “coalesced” cracks, their number, and moreover, blocks of pixels belonging to them.

Then a frame grid with square meshes is superimposed on the images \( \Phi \) and \( \Psi \), and at the points of its intersection with crack areas (the image \( \Psi \)), the location of nodal points is calculated. In so doing, the location of every nodal point corresponds to the image area of the maximum intensity (the image \( \Phi \)). The grid spacing is chosen such that the obtained set of nodal points should represent the location and shape of cracks adequately. The subimages whose dimensions are less than a certain minimum value are neglected. In the general case, the grid spacing should be about the half of the crack thickness.

For nodal points, the most probable direction of the crack is calculated. To this end, a search for the longest segment of the crack that goes through it and is within its area (i.e., is within the limits of the single picture elements of the image \( \Psi \)) is conducted for every point. The direction (the angle in the Cartesian coordinate system) of the longest segment is considered to be the most probable direction of the crack propagation for the given nodal point. Further, based on the analysis of the proximity of the obtained angles of the crack propagation, chains of interrelated points are found that reflect the crack direction and location.

The resulting set of segments obtained during previous calculations can contain meaningless fragments or reflect the location of the crack not in full measure. Therefore, the segments that are shorter than some limiting value are eliminated from it. Then, for every finite crack segment, its “extension” is performed so that it is within the boundaries of the crack fragment of the image \( \Psi \).

The algorithm of crack search and analysis has a number of input parameters directly influencing the result of the software operation. Therefore, it is of importance to assess their effect on the qualitative and quantitative indices of the object surface degradation in order to avoid wrong conclusions and artifacts. The analysis of the effect of these parameters will make it possible to select them so that the operation of the algorithm for this set of images is the most efficient. For consistent assessment of the dynamics of the variation in the values analyzed, the analysis of a number of photographs of the BCCM roll was made for different values of the studied parameters of the proposed algorithm. The images analyzed measure 1000 by 640 pixels, the resolution is 600 points per
As a result, the algorithm of crack analysis calculates the following parameters: 1) the area of cracks; 2) the number and length of straight segments by which cracks are approximated; 3) the number of coalesced cracks. To provide a qualitative and quantitative characterization of the degree of fracture of the surface under study, the developed software produces: angular and segmented recordings of the distribution of straight crack segments in the direction of propagation (in the system of the image coordinates); a bar diagram of the distribution of straight crack segments (in this case, the relative unit of length - the frame grid spacing - is used).

3 The effect of the filter kernel size.
An important step of the BCCM roll photo image analysis algorithm is filtration that makes it possible to avoid the effect of noise components and to produce a complete picture of cracks. The filtration is carried out by smoothing of an output binary image using a linear balanced smoothing filter with a square kernel. Therefore, the filter kernel size $L_G$ influences directly the general view of the obtained picture. A decrease in sharp transitions in the luminance levels that are typical of the random noise is attained by replacing the output values of pixels by the filter kernel average values.

An important feature of filtering is the image defocusing that makes it possible to produce a coarse image of crack objects. In so doing, the intensity of small objects is merged into the background, whereas great objects remain and can be identified easily. The size of the objects that are merged into the background approximately coincides with that of the filter kernel.

Thus, the operation of filtering allows one to reveal the geometrically near segments of the crack and integrate them, even though they are separated by the background space in the output binary image $B$. The degree of “coalescence” of adjacent segments depends on the size of the filter kernel. The greater it is, the stronger is the coalescence of separate segments and the greater is the distance of influence of one crack segment on another. Therefore, the value of the kernel size should be chosen such that it is considerably less than the distance between separate cracks but greater than possible noise bands of the background that are improperly superimposed upon the crack picture. The influence of the parameter under consideration on the process of crack edge definition is seen from Fig. 2. A too low value of the kernel does not remove a great number of noise elements (Fig. 2 a). A too high value results in the distortion of crack shapes and the exceeding of their calculated areas at the expense of merging of adjacent background segments (Fig. 2 c). In this case, the spacing between separate segments located nearby increases too.

![Image](image.png)

Fig. 2. The influence of the filter kernel on the result of crack localization for the image of Fig. 1a: a) the kernel size is 5 pixels (a great number of noise elements); b) the kernel size is 10 pixels (normal recognition); c) the kernel size is 20 pixels (the growth of crack areas, partition of separate segments)

In constructing the graph of the variation in the parameters analyzed (crack areas, the number of the straight fragments of cracks and the number of coalesced cracks) versus the kernel size, a stable decrease in the number of straight fragments with the increase in $L_G$ can be seen, Fig. 3 a.
This fact comes from the nature of filtering itself: an increase in the level of smoothing of the image results in the increase in the dimensions and areas of fragments, due to which they are merged, enlarged and approximated by the less number of segments. In this case, the variation in the size of the filter window affects the number of the identified coalesced cracks and the total area of the cracks only slightly, Fig. 3a. The data of the experimental investigations show that for a selected set of images, there exists the optimum range of the values $L_G = 8$ to 12. This reflects, to a certain extent, both the specific feature of the given area of the roll surface and the chosen way of producing the resulting image.

The nonuniformity of crack distribution results in the formation of their clusters. In this way, the cracking structure occurs that is responsible for the material properties. Thus, if the primary element under study is a crack, then the structural unit is a cluster of cracks, since it is the structure of cracks that is responsible for the stress distribution on the construction surface [5, 8]. Analyzing the effect of the parameter $L_G$ on the number of “coalesced” cracks, the authors have revealed that it is of low sensitivity to the variation in the size of the filter kernel in the range under study, Fig. 3a.

The number of unfound cracks is low amounting to 1 or 2 pieces for the whole range of the investigated values of $L_G$, Fig. 3b. The length of the omitted fragments of the frame grid has two maximums for the lowest and highest values of the studied range of $L_G$. However, within them the values of this quantity vary slightly from 10 to 15 units, Fig. 1c.

The effect of the background boundary. To search for crack borders, the filtered image $\Phi$ is binarized through the comparison with a certain boundary value, as a result of which the matrix is produced wherein the zero values correspond to the background and the unit ones to crack objects. The matrix of that kind can be represented as the black-and-white picture $\Psi$ wherein black objects are located on the white background. The indicated boundary value is adaptive and specified in percent relative to the intensity scatter in the filtered image. Since the subsequent search for cracks is conducted through the analysis of the image $\Psi$, the parameter under consideration strongly affects the process of their localization.

In this case, the circumstance that the background boundary goes beyond the optimum range results very quickly in significant errors in the search for cracks (Fig. 4). If this boundary is too small, then a
considerable part of the background will be added to cracks, due to which a great number of phantom crack objects will be revealed (Fig. 4a).

In the case where the value of this boundary is too high, the part of the image that really belongs to the crack will be considered as the background (Fig. 4c). This will result in escaping a certain part of objects, especially of small geometries, from the field of the search algorithm, as a result of which the appropriate cracks (or their parts) will not be found. The specific value of the parameter under consideration depends on the specimen type, conditions for producing the resulting image (illumination, in particular), the photographic camera specifications and the parameters of the selected digital filter.

It has been found experimentally that for the set of images under consideration and the selected filter, the optimum value of the background boundary is about 30%. The algorithm operation is deteriorated slightly if the value of that parameter varies within the limits of ±10%.

The graph of the results of the algorithm operation versus the background boundary value is given in Fig. 4d.

The effect of the frame grid spacing. Based on the produced filtered image and its processing, the search for crack nodal points is conducted that are used subsequently in the image modeling, Fig. 1b. For this purpose, the frame grid with square meshes is superimposed on the image produced after smoothing, and the location of nodal points is calculated at its intersections with crack areas.

In the general case, the increase in the frame grid spacing results in the increase in the computation error of crack characterization, Fig. 3b. Since the search for cracks is made using the least-square approximation of clusters of points, the increase in the grid spacing inversely affects the number of straight crack fragments, Fig. 3b. The increase in the number of straight fragments is primarily caused by the possibility of identifying several straight fragments detected at a lesser spacing as a single fragment detected at enlarged grid spacing.

Besides, peaks are noticeable in the curves of variation in the number of unfound cracks versus the parameter under study, Fig. 3d, which are the characteristic feature of the given surface area and are dependent, in particular, on the degree of the crack branching.

The effect of the slope angle proximity. In the search for cracks, an approach is used that consists in constructing the model of an individualized crack object. Clusters of points are identified in the image, after which a subset of points is separated from a certain number of points of an ideal model. For that subset it is necessary to take measurements of the
coordinates in a real image. The location of points is dependent on the peculiar features of the specific object and is of prime importance in its recognition from the image, Fig. 1b.

For this purpose the most probable crack direction characterized by a certain angle $\phi_k$ is calculated for each of the nodal points. This parameter is used for grouping points into clusters that belong to one crack. In doing so, the comparison is made between the angles $\phi_k$ of adjacent points and a certain boundary value of $\Delta \phi_k$.

In this manner, the chains of adjacent interrelated nodal points are revealed that belong to the appropriate cracks. The nodal points of every crack are grouped into a separate cluster, which makes it possible to simply approximate them later on by straight segments within a prescribed accuracy.

The conducted experimental investigations have shown that the above-mentioned parameter slightly affects the results of the algorithm operation (Fig. 5), which is attributable to good identification of nodal points at previous stages of the image processing. Only with sharp deviations in the proximity of the angle $\Delta \phi_k$ from the optimum range, a drastic increase in the errors of crack recognition is observed.

The effect of other parameters. During the algorithm operation, a set of additional parameters is used, namely, the minimum permissible geometrical dimension and the square of the identified object, the allowable value of the spacing between fragments of a single crack, the approximation accuracy, etc. The investigations have shown that these parameters affect slightly the result of crack detection in the image.

**Conclusions**

A general structure of the software for producing, processing, analyzing and documenting digital images in the optical crack detection has been considered. The main components of the algorithm to detect crack locations have been presented and its investigation has been carried out using a number of images of the BCCM roll fragment. Distortions occurring at each of the stages of data processing have been described and analyzed, and the main factors influencing the accuracy of measurement have been revealed. For the procedure proposed, these are the following factors: the filter properties, background boundary and value of the frame grid discretization.

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**References:**


