The algorithm of crack and crack tip coordinates detection in optical images during fatigue test

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Abstract. An algorithm of crack detection during fatigue testing of materials, designed to automate the process of cyclic loading and tracking the crack tip, is proposed and tested. The ultimate goal of the study is aimed at controlling the displacements of the optical system with regard to the specimen under fatigue loading to ensure observation of the 'area of interest'. It is shown that the image region that contains the crack may be detected and positioned with an average error of 1.93%. In terms of determining the crack tip position, the algorithm provides the accuracy of its localization with the average error value of 56 pixels.

1. Introduction

When studying the fatigue fracture of solids, the problem of estimating crack growth parameters (length, growth rate, crack opening displacement, etc.) is one of the most important. Thus, the tracking of the fatigue crack tip is an actual engineering problem. The issues of fatigue failure, as well as the problems of mutual influence of the damage accumulation process and stress-strain state evolution in the vicinity of the crack tip, have been constantly attracting the attention of researchers from the ancient times and are of fundamental and practical importance today [1]. For example, in [2] the basic regularities of deformation and damage accumulation processes are summarized and mathematical models to describe this process development are presented.

Currently, a contactless strain measurement optical system is widely used, since it enables quantitative analysis of the fatigue crack growth characteristics and recording of strain distribution patterns in the vicinity of the crack tip. The commercial systems, like VIC 3D, Strain Master [3, 4] and others first of all in their stereoscopic realization have become very popular for appreciable aiding the experimental mechanics. These systems comprise a pair of TV cameras operating in a macro shooting mode. They are usually aimed at obtaining the macroscale pattern of strain distribution on the surface of the specimen under loading. At the same time, from the point of view of physical mesomechanics and fracture mechanics, the studies involving the crack with the length not exceeding tens of microns are of particular interest. In this case, the crack growth observation at macroscale is impossible because the spatial resolution does not resolve the crack as well as the processes developing at its tip.

To solve this problem, optical microscopes with a photo or video camera attached are employed. However, when using high magnification of the optical microscope with the cyclic loading, a fatigue crack tip will constantly go outside the observation area. In this concern, it is necessary to design a

IOP Conf. Series: Materials Science and Engineering **177** (2017) 012019 doi:10.1088/1757-899X/177/1/012019

hardware/software setup (systems) that allows controlling the mechanical scanner, which displaces the optical system (comprising a microscope and video camera) in relation to the sample surface where the crack tip is to be detected and located. In this paper, the problem of image analysis algorithm development was solved in order to ensure fast crack detection by a series of images for further decision-making on the magnitude and direction of the displacement of the optical tracking system.

The literature reports on several different methods available for crack detection including image-processing methods (wavelet and Fourier transforms, Canny filters, Sobel filters, etc.) [5], percolation-based techniques [6–8], impact echo method [9], PCA-based techniques [10], etc. Automated crack inspection systems were developed in adjacent engineering areas [11], where the Laplacian of Gaussian algorithms have been implemented. Stereovision techniques have been used in automated distress survey systems [12]. Another crack detection scheme makes use of maximum a posteriori (map) classifier, which relies on a set of geometric characteristics of the segmented binary regions [13].

2. Crack detection

The crack detection algorithm proposed in this paper consists of two approaches: 1) analysis of the image pairs (series) based on data of objects motion; 2) analysis of individual images based on the contour detection. Let us consider each of them in detail.

2.1. The analysis of image pairs (series) based on data of objects motion.

When analyzing an image series (or video sequence) that illustrates the crack growth, key information can be extracted from the analyzed motion of image fragments. In this case, the surface texture is of low informativeness, since it mostly allows improving the reliability (accuracy and noise robustness) during displacement determination. For further analysis, the data on the optical flow resulted from the discontinuity (crack) growth are used. Thus, the object of the analysis is the pattern of the optical flow (Figure 1a), where a discontinuity (abrupt variation in displacements at the edges of the opening crack) has to indicate the presence of the crack.

However, the opening displacement values for short cracks can make only a few pixels; in this case, for the purpose of additional contrasting (edge enhancement), the optical flow differentiation procedure is applied (Figure 1b). Its implementation is realized with the help of Sobel operator for a window size of 3x3 [14]. Remarkably, the use of the first approach results in a number of errors due to inherent errors of optical flow determination algorithms. For this reason, the first approach to crack detection can be used for the initial (coarse) detection of the image region where a crack might present (Figure 1c).

a b c

Figure 1. Crack detection by the analysis of the image series based on object motion data: (a) the optical flow pattern; (b) differentiation of the optical flow; (c) selecting the region of probable crack location

2.2. The analysis of individual images based on contour detection.

During the processing of single images (without considering other images in the series or a video stream), the information about the surface texture is analyzed (Figure 2a). In the process of crack tracking, two key tasks are to be solved: 1) detection of a crack in the image and 2) determination of its location. It is implemented through image contour analysis, which is based on the decomposition of the 'scene' into individual objects and the background (Figure 2b) (segmentation). The use of the contour analysis makes it possible to allocate small crack-like objects (Figure 2c). During the

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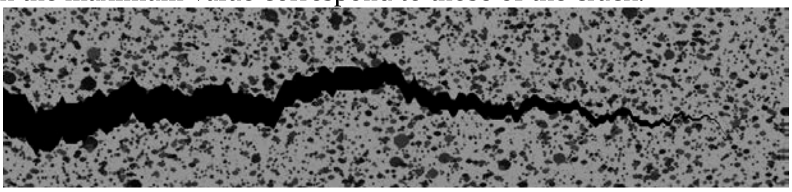
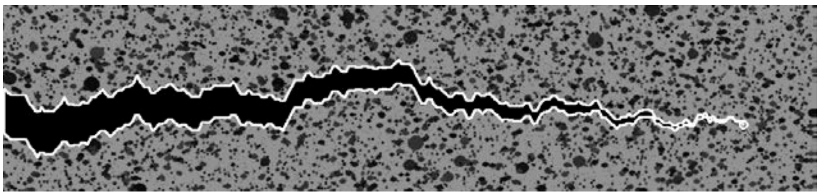
segmentation, a large number of objects are detected, while only one or a few of them are the cracks indeed.

It is a priori known that a crack appears as the darkest object in an image. In order to reduce computational costs and to increase the robustness of the crack detection, the developed algorithm employs binarization that makes it possible to reduce the amount of objects under analysis. In doing so, the binarization algorithm is based on histogram analysis with the determination of the (global) brightness threshold value. It is related to the fact that the threshold value mostly corresponds to low brightness levels. Subsequent processing of the resulting black-and-white image is related to the use of the ‘morphological closing’ operation. It is aimed at removing small dark fragments in the image that correspond to surface texture elements, but do not belong to the crack(s). Then, the resulting black and white image is subjected to contour analysis in order to detect the object(s), whose geometrical characteristics in the maximum value correspond to those of the crack.



a

b



c

Figure 2. Crack detection by the analysis of individual images based on the contour detection: (a) input image; (b) binarized image used for segmentation; (c) detected crack

2.3. Crack tip detection.

A region in the image corresponding to the crack tip is usually of low contrast. Hence, the procedure of determining its exact coordinates is a separate challenge. It is proposed to construct the skeleton [15] of crack-like objects with subsequent assessment of the crack opening value towards the axis of the skeleton. For the crack skeleton construction, the shortest distance from the point inside the crack towards its boundaries (faces) is evaluated (Figure 3). It is based on the fact that the crack skeleton represents a curve that combines the points with the maximum values of the estimated distance.

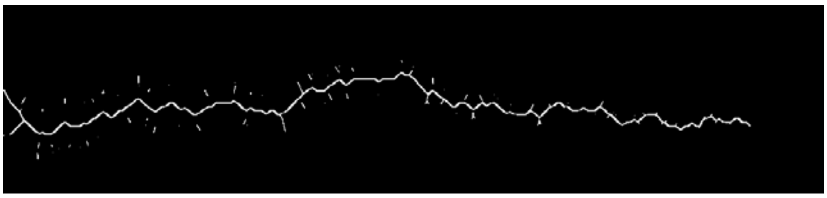


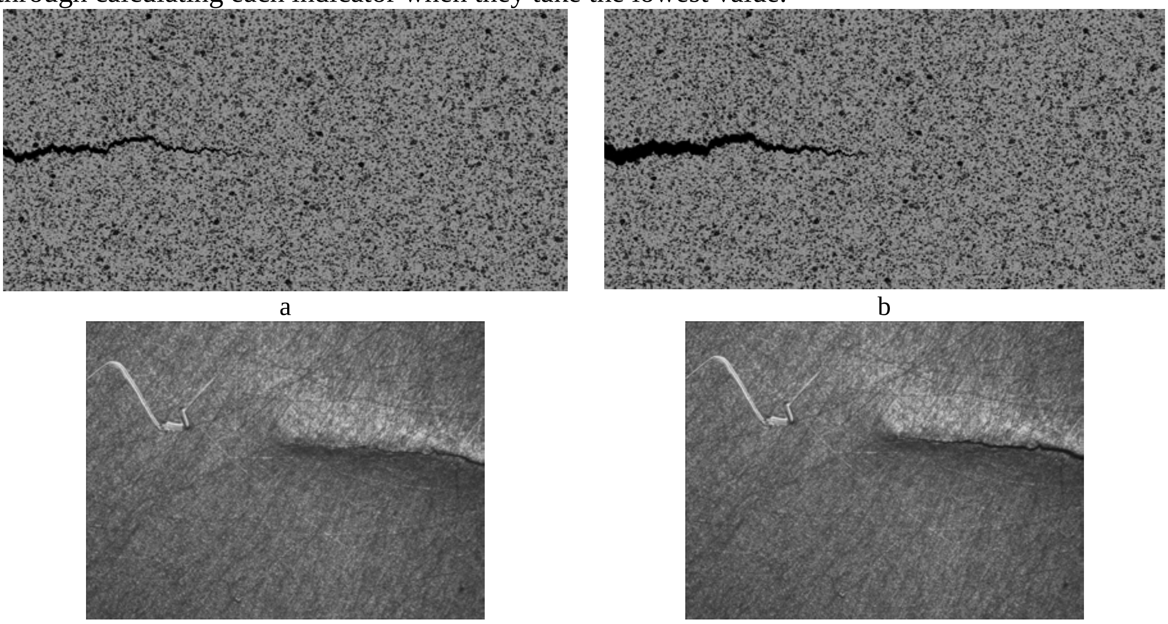
Figure 3. The crack skeleton.

3. Testing

The developed algorithm was tested with the use of a model image series. The efficiency of the algorithm was first evaluated in the absence of external perturbations (noise, geometric distortion, etc.). The model image series was formed as a textured surface (simulating a sprayed speckle) with software-assisted superimposition of a crack (Figure 4 a, b). The construction of the model images was made in several stages: 1) synthesis of the material surface model (speckle image formation); 2) setting the crack parameters (length, opening, shape of edges that imitate its branching); 3) material model variation (image distorting) with respect to the change in crack parameters.

In addition, in order to determine the robustness of the proposed algorithm, the model images were distorted by blurring and noising (to imitate the distortion specific for image acquisition in laboratory experiments). Also, crack detection was carried out when processing experimental images (Figure 4 c, d) made under cyclic tension of aluminum alloy 2024.

To assess the effectiveness of the crack detection algorithm, two measures were introduced: 1) the difference between the coordinates of the crack tip in the model image (a known value) and those determined with the use of the algorithm (see Section 2); 2) the difference between the crack area (the principle of the calculation is given in Sec. 2) detected using the proposed algorithm and that known from the model image. The correctness level of the proposed algorithm functioning might be evaluated through calculating each indicator when they take the lowest value.



a b c d

Figure 4. Model (a, b) and experimental (c, d) images illustrating the crack growth.

4. Results and discussion

The results of the algorithm testing based on the calculation of the above introduced measures are shown in Figure 5. At first, the comparison of the area of the algorithm-detected crack against the model value was performed. Then, the detected crack tip coordinates were compared against known (model) ones. Figure 5 also illustrates the results of crack detection when various levels of noise and blur were applied to the model images.

The results of model image processing (including blurred and noisy ones) have shown that the algorithm is capable of determining the coordinates of the crack tip with the average error of 56 pixels. During the crack area determination, the algorithm ensures the accuracy to locate its position (including edges) with an average error of about 1.93%.

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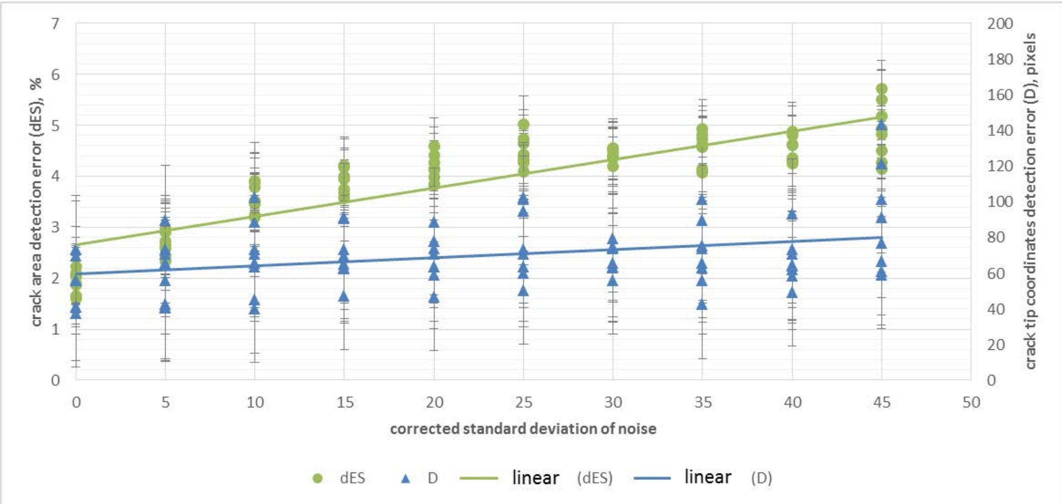
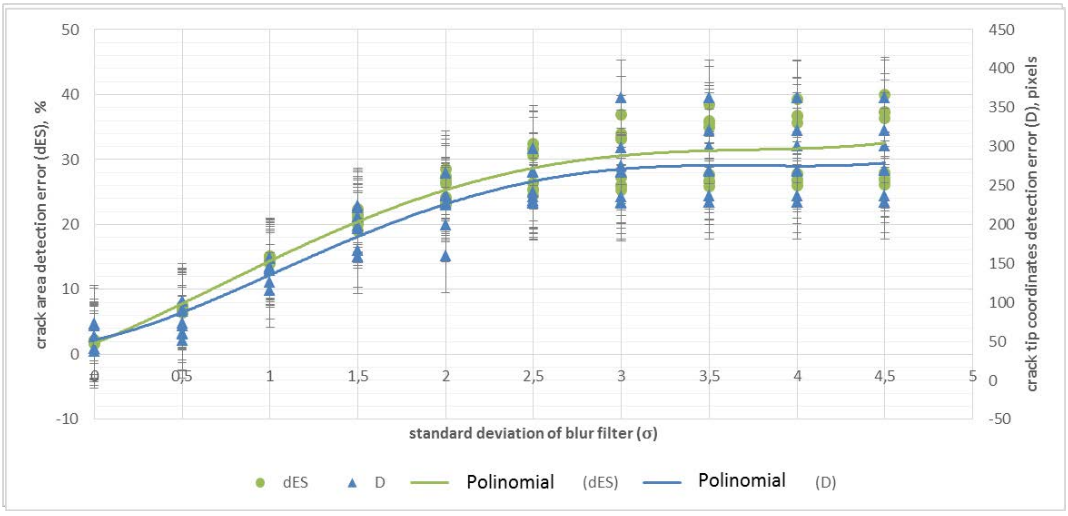
During testing 8 pairs of model images were generated, thus a statistical characteristic could be obtained. Figure 5 shows the standard deviation of the crack area detection error equal to 0.21% and the standard deviation of the crack tip coordinates detection error equal to 15 pixels from its average value.

The analysis of the data presented in Figure 5 shows that the proposed algorithm gains a maximum error of crack allocation equal to 5.7% when noisy images (s = 45) are processed, while the error increases sharply under their blurring and reaches 40% when the blur filter with σ = 4.5 is employed.

In the case of crack tip positioning, the trend of an error increase persists for both noisy and blurry images. However, the model images have the size of 2000×1000 pixels (which corresponds to their diagonal length of 2236 pixels), while the maximum error of coordinate determination is about 350 pixels. It makes only 15% of the diagonal length of the entire image. Therefore, this error value would not significantly affect the accuracy of the optical system positioning during the tracking of a fatigue crack.



a



b

Figure 5. Plots of the crack and crack tip detection under noise (a) and blur (b).

The result of crack detection in the experimental images is shown in Figure 6. It is seen that the contour delineates precisely the crack edges. Thus, the possibility of applying the proposed algorithm to solve the problems of crack detection in optical images was proven for both model and experimental images.

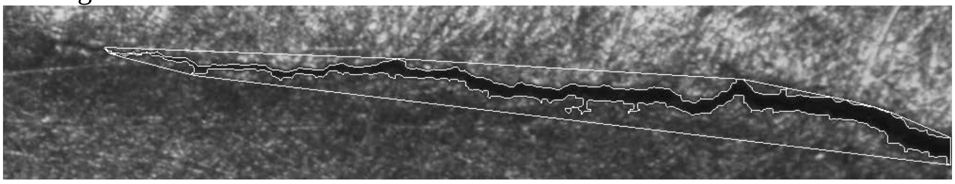


Figure 6. A crack detected in the experimental image.

5. Conclusion

The algorithm for automatic crack and crack tip detection in optical images under fatigue testing was developed and tested. The results on model image processing (including blurred and noisy ones) have shown that the algorithm is capable of determining the coordinates of the crack tip with the average error of 56 pixels. During the crack area determination, the algorithm ensures the accuracy to locate its position (including edges) with an average error of about 1.93%. The maximum error of crack area location is 5.7% for noise content, but it rapidly increases for blurred one and is equal to 40%. Accurate performance of the developed algorithm under processing of experimental images was proven. The developed algorithm will be used to solve problems of fatigue crack tracking automation when large magnification of the optical system is used.

Acknowledgments

The work was conducted as a part of the program of fundamental researches of the State Academies of Sciences (PFR SAS) for 2013-2020 No. 23.1.3, as well as RFBR grant No. 16-38-00526, and the grant of the President of the RF No. SP-1529.2015.5. Authors acknowledge A V Eremin for provided optical images and participating in results discussion.

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