STRAIN ANALYSES OF NONLINEAR CRACK BEHAVIOR AT ELEVATED TEMPERATURE BY FINITE ELEMENT METHOD AND MOIRÉ TOPOGRAPHICAL METHOD

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The advanced reactors, such as breeder reactor and high temperature gas-cooled reactor, are designed to operate at the elevated temperature, which is expected to be above the transient temperature of creep. In order to evaluate the safety and integrity of those reactors, there need the nonlinear analyses of flaws under the elevated temperature with consideration of creep phenomena. As the experimental measurement of strain under the elevated temperature seems much more difficult than that around the room temperature, most of methods which have been commonly used, may lose their validity, e.g. the usual strain gauge method has such instability and insensitivity at high temperature that it is almost impossible to analyze the structural nonlinear behavior experimentally.

In this paper, a new measurement scheme for strain analyses is presented: the Moiré topographical method aided by picture processing with the use of computer. The picture processing technique enables us to analyze nonlinear behavior of crack growth under elevated temperature from two different points of view: (1) Macroscopic measurement of crack growth (2) Microscopic analyses of the displacement and strain distributions at the crack tip field. In the macroscopic measurement of crack growth, some of the fundamental processing schemes, registration and edge-enhancement (thresholding) are available to measure the extension of crack length and crack opening displacement. Through this measurement, we can obtain the crack growth curve and the relation between crack propagation rate and mechanical fracture parameter such as stress intensity factor or J contour integral value. In the microscopic analyses of the displacement and strain distributions at the near crack tip field, we have found that a series of processing algorisms is useful to eliminate the noises from the original picture, elaborate the synthesized Moiré fringe pattern and make fine strain analyses. These processing algorisms consist of

(1) Bandpass filtering (2) Multiplication between noiseless picture and master grids
(3) Thinning of Moiré fringes (4) Automatic count of the number of Moiré fringes
(5) Translation from the fringe pattern to displacement and strain distribution

Finally the finite element methods are utilized to calculate the creep crack growth with the large-displacement formulation. Simulating the experimental crack growth curve and comparing F. E. M. results with the above experimental ones, we have found that Moiré topographical method is so useful as the strain measurement technique in the high temperature environment that it could make clear the important effect of the deformation around the crack tip on crack behavior under the elevated temperature.

1. INTRODUCTION

In the design of advanced nuclear reactors such as breeder reactor or high temperature gas-cooled one, it is of great importance for structural engineers to consider the various effects caused by creep phenomena, especially to evaluate the safety and integrity of material in the elevated temperature. Although the recent development of linear fracture mechanics may enable us to estimate the crack behavior, the time-dependent deformation near the crack in the structure is still problem to be studied as the operating temperature increases. In case the materials show a power law relation: $\dot{\varepsilon} = \kappa\sigma^n$ in the stationary creep range, the creep strain rate tensor near the crack tip is written according to the nonlinear fracture mechanics [(1)] as follows: $\dot{\varepsilon}_{ij} = \kappa\left(\frac{J}{\kappa I r}\right)^{\frac{n}{n+1}} g_{ij}(\theta, n)$
where r and θ are the polar coordinates at the crack tip, I is the constant which is dependent on n, g_{ij} is the characteristic function and J is the contour integral value around the crack tip which is defined under stationary creep. From the theoretical investigation, it is also inferred that J is an effective characterizing parameter for the near crack tip. Experimental investigation reveals that J integral value may correlate with the crack propagation rate better than other parameters may. This fact tells us J is really one parameter which can describe the crack behavior. But the existence of singular strain field which relates with J value has been made clear neither by the macroscopic measurement of crack extension nor the metallurgical observation of microstructure.

With the use of the Moiré topographical method together with the digital picture processing (Digital Moiré Method), the displacement and strain distributions in the vicinity of crack tip will be obtained in this paper.

2. PROCEDURE OF THE CRACK GROWTH MEASUREMENT AND DIGITAL MOIRÉ METHOD

The conventional measurement of crack growth is performed by eyesight which makes the results less accurate. Under the elevated temperature, both measurements by telescope [(2)] and the electric potential method [(3)] have been available ones until the present alternative appears. In order to overcome the inaccuracies and to make longterm experiment possible, the easy and compact procedure for crack growth measurement is also needed. The picture processing enables us to make more accurate measurement of crack length. There are two typical processing schemes: on-line processing and off-line processing. In the present experiment, the latter one is adopted and the original photos which are taken during experiment, are scanned by optical transducer, registered into the coordinate system and the crack porfile is extracted with the use of edge-enhancement [(4)].

The Moiré topographical method [(5)] is one of the most effective measurements of strain distributions under the elevated temperature. For the strain analysis under elevated temperature, the special apparatus including the heat-proof Moiré camera [(6)] is necessary. Even if we could use this special apparatus, there remains the fatal weak point intrinsic to the Moiré topographical methods: transformation from the Moiré fringe pattern to strain distributions must be done manually. Here, we propose the effective method, where the Moire fringe pattern is synthesized digitally from the deformed Moiré grids and the strain and displacement distributions are obtained from the Moiré fringe pattern by the computer manipulations (this method is named here Digital Moiré Method). In order to explain the present method we illustrate the typical picture-processing procedures as are shown in photos

1 to 4. It is known that one can obtain Moiré fringe with the Moiré topographical method for the specimen under any loads. As seen from photos 1 and 2, the addition of the deformed grids to the standard ones can bring the Moiré fringes. The synthesized Moiré fringes are mixed with other pseudo ones as depicted in photo 3a. In order to extract only Moiré fringes, a series of processing is needed; edge-enhancement, isolation and flatting of neighborhoods or thinning of fringes. The above procedure can pick up the Moiré fringes only, as is shown in photos 3 and 4.

3. TENSION TEST OF CRACKED PLATE AT ELEVATED TEMPERATURE

3.1 Experimental apparatus: The furnace of boxed type with thermal controller can hold the temperature of test specimen at 650°c. For the fulfilment of uniform loading, universal tensile test machine is used with servomechanism, which keeps the fluctuation of load between ± 0.1 %. Schematic view of experimental apparatus is shown in Fig. 1.

3.2 Test specimen and Moiré grids: The thin plate of type 304 stainless steel is used as the test specimen, which is shown in Fig. 2. The initial crack is sharpened by high-cycle fatigue test. To obtain the stable grids at high temperature, the following series of treatments is found to be suitable: optical exposure during 30 seconds, curing treatment and chemical etching during 120 seconds by 5 % dilute oxalic acid. The mesh size of standard grids is 250 per inch.

4. MACROSCOPIC MEASUREMENT OF CRACK GROWTH

4.1 Fundamental technique of crack growth measurement: The fundamental technique used here is edge-enhancement or thresholding: four points a, b, c, and d shown in photo 5 are chosen to calculate the origin and directions of coordinates system. Photo 6 shows the picture ante and post the edge-enhancement. The crack profile is extracted from the original picture, so that we can measure easily the crack length, etc.

4.2 Experimental results: From the successive measurement of crack length the crack growth seems to be represented as a function of nondimensional time T/T_f as is shown in Fig. 3. The study of relation of crack propagation rate with three typical mechanical parameters, i.e. the stress intensity factor, the net section stress and the J contour integral value reveals that two former parameters may have some correlations, but the linearity of J vs. propagation rate assures the J contour integral value is more suitable to describe the crack growth phenomena under elevated temperature (see Fig. 4).

5. MICROSCOPIC ANALYSIS OF THE DISPLACEMENT AND STRAIN DISTRIBUTIONS AT THE NEAR CRACK TIP

5.1 Picture processing procedure for digital Moiré method: The typical picture processing procedure for digital Moiré method is illustrated in photo 7. After the original photo taken during experiment is scanned into half-tone picture and registrated, the bandpass filtering method is used to eliminate the low- and high-frequency noises with the help of fast Fourier transformation. The Moiré fringe pattern synthesized from the original photo taken just after application of load is shown in photo 7d.

5.2 Experimental results: In order to study how the displacement and strain distributions in the vicinity of crack tip change as time elapses, the photos taken at T = 0.0, 3.8 and 11.0 hours are processed with the use of the above mentioned techniques. The synthesized

Moiré fringe patterns in case T = 3.8 and 11.0 hours are shown in photos 8a and 8b. The comparison between two Moiré fringes reveals that the crack tip area continues to deform as the time elapses and the crack continues its propagation and that strains concentrate much at the near crack tip when the material becomes under stationary creep condition with crack growth. For fine strain analysis is needed the elaboration of Moiré fringe pattern. As the use of mismatched grids is known to be the improvement scheme of accuracy of Moiré methods, it is noted that digital mismatching method will improve the accuracy. Comparing the fringe pattern synthesized by the usual grids with that by mismatched ones, it is found that the number of Moiré fringes increases in the same area with the use of mismatching, as is shown in photo 9.

6. CONCLUSIONS

The simple digital picture processing which is called edge-enhancement or thresholding, is found to make it possible to measure the crack profile rather clearly, even if the original picture is not so fine enough to determine the figure of crack. Moreover, the Moiré topographical method together with the digital picture processing (Digital Moiré Method) is proved to be very effective to make fine and accurate strain analyses of the crack in the material under elevated temperature.

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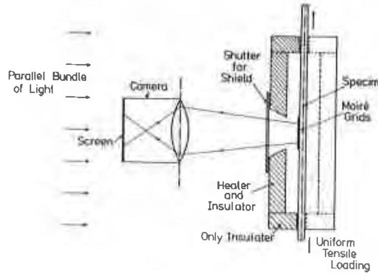


Fig. 1 Schematic figure of apparatus

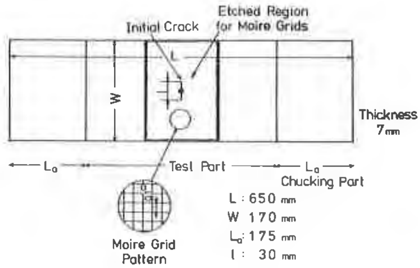


Fig. 2 Specimen and Moiré grids etched on the surface of specimen

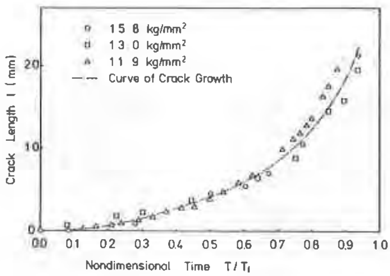


Fig. 3 Relation of crack length l and nondimensional time, T/T_f, where T_f is the creep rupture time of each specimen.

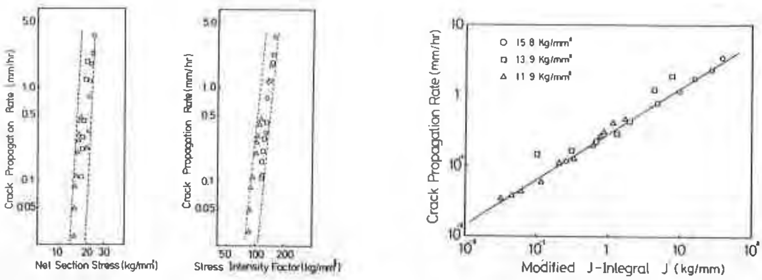


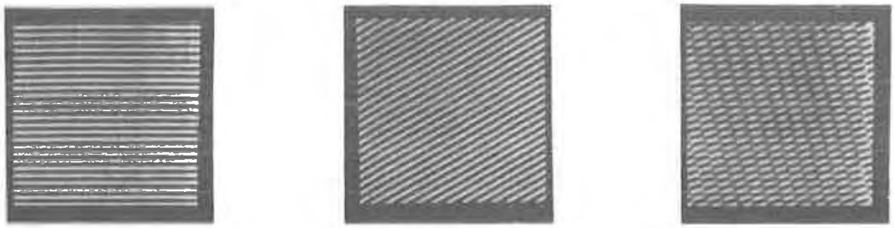
Fig. 4 Relations of crack propagation rate dl/dt to three typical fracture parameters: in the left figure, dl/dt vs. the net section stress, in the middle one, dl/dt vs. the stress intensity factor and in the right, dl/dt vs. the J contour integral value.

1a. Standard grids pattern (T = 5.12)

1b. Deformed grids pattern under uniform compressive force (T = 4.27)

1c. Synthesized Moiré fringe pattern

Photo 1. A series of pictures which are processed with the aid of computer (Test 1): in case that standard grids pattern is under compressive force.



a. Standard grids pattern

b. Deformed grids pattern rotated with angle $\alpha = 30^\circ$

c. Synthesized Moiré fringe pattern

Photo 2. A series of pictures which are processed with the aid of computer (Test 2): in case that standard grids pattern is rigidly rotated with angle $\alpha = 30^\circ$

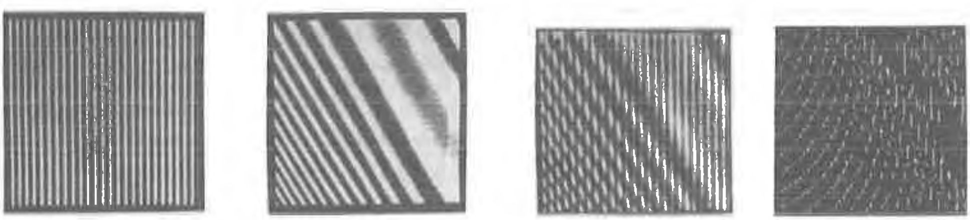
a. Synthesized Moiré fringe pattern

b. Picture after edge-enhancement (thresholding)

c. Picture after elimination of isolated points

d. Picture after the conventional neighboring algorism (3 x 3)

Photo 3. Thinning technique of Moiré fringe pattern (Test 2) which is synthesized by present method

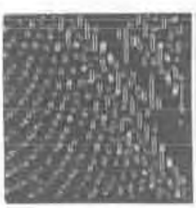


a. Standard grids pattern

b. Deformed grids pattern rotated and linearly strained

c. Synthesized Moiré fringe pattern

d. Picture after edge-enhancement and elimination of isolated points



e. Picture after the conventional neighboring algorism (3 x 3)

Photo 4. A series of pictures which are all processed with aid of computer (Test 3): in case that standard grids pattern is rigidly rotated with angle $\alpha = 30^\circ$ and, after that, becomes under linearly varying strain.

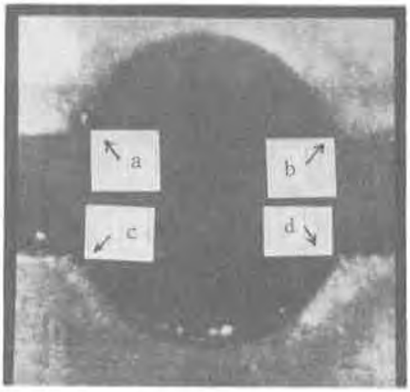
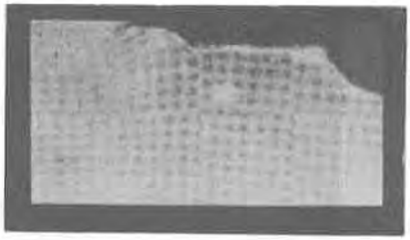


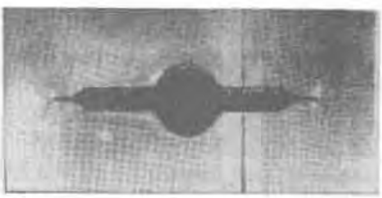
Photo 5. A picture of circular hole drilled at the center of crack: four points indicated in the picture, a, b, c and d are used for registration.



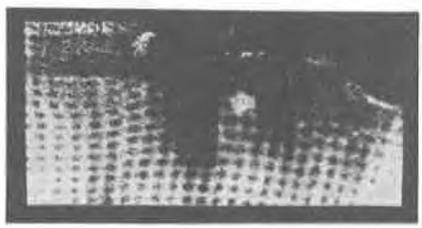
6a. A picture prior to the edge-enhancement.

6b. A picture posterior to the edge-enhancement (threshold value is 100)

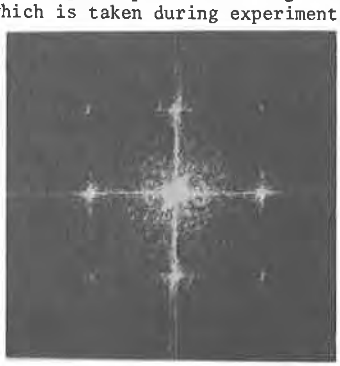
Photo 6. Typical picture processing for macroscopic measurement of crack growth.



7a. The original photo including a crack, which is taken during experiment.



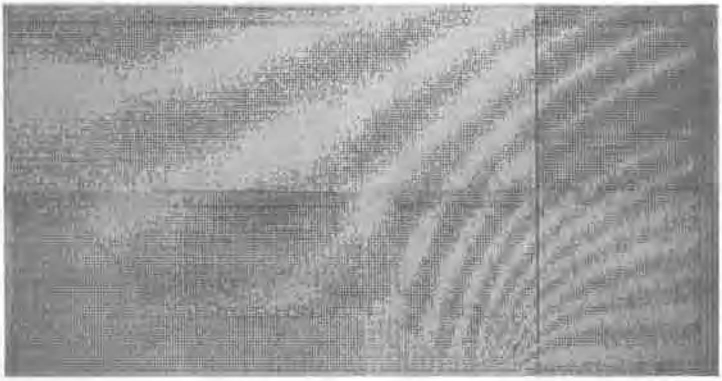
7b. The scannned and registrated picture.



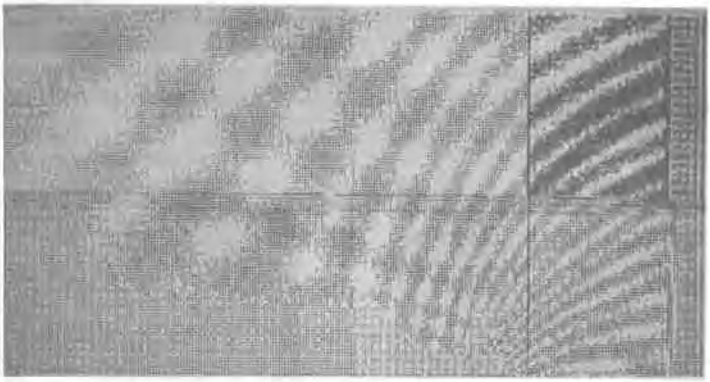
7c. Typical power spectrum of Fourier transformed picture.

7d. The synthesized Moiré fringe pattern.

Photo 7. The present picture processing procedure for Digital Moiré Method to analyze the crack behavior in the vicinity of crack tip: in case that the test specimen is just loaded under elevated temperature (650°C).

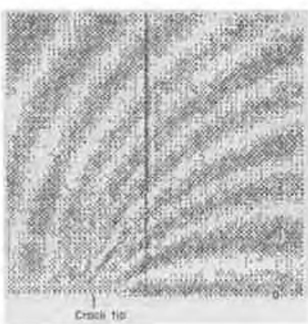


8a. The synthesized Moiré fringe pattern in case that 3.8 hours (T / T_f = 0.08) have elapsed and the material is still under transient creep condition without crack growth.



8b. The synthesized Moiré fringe pattern in case that 11.0 hours (T / T_f = 0.23) have elapsed and the material becomes under stationary creep condition with crack growth.

Photo 8. Some Moiré fringe patterns synthesized by Digital Moiré Method: in photo 8a, Moiré fringe pattern in the vicinity of crack tip under transient condition and in photo 8b under stationary condition.



9a. Moiré fringe pattern without mismatching.

9b. Moiré fringe pattern with some mismatching (s = 2 %).

Photo 9. Elaboration of Moiré fringe pattern by the digital mismatching.