

Influence of environmental factors on corrosion damage of aircraft structure

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Abstract Corrosion is one of the important structural integrity concerns of aging aircraft, and it is estimated that a significant portion of airframe maintenance budgets is directed towards corrosion-related problems for both military and commercial aircraft. In order to better understand how environmental factors influence the corrosion damage initiation and propagation on aircraft structure and to predict pre-corrosion test pieces of fatigue life and structural integrity of an effective approach, this paper uses the cellular automaton (CA) method to character the effect of electrolyte concentrations, dissolution probabilities, and temperature on the corrosion damage of a metal structure exposed to an aggressive environment, and the procedure for applying the local rules between the cells of the CA to simulate the corrosion damage evolution is formulated. The simulation results show that the different electrolyte concentrations, dissolution probabilities and temperature, the laws of the dissolution current with time are investigated and they obey the time power function. © 2011 The Chinese Society of Theoretical and Applied Mechanics. [doi:10.1063/2.1106104]

Keywords aircraft structure, corrosion damage, environmental factors, cellular automaton, simulations

Corrosion is one of the serious problems affecting airforce and other aviation industries. It affects the aircraft on its wings, surface, between joints and fasteners.¹ In corrosion environment, because of chemical and electrochemical reaction between surrounding medium and material elements, it is easy to form several different forms of corrosion on the surface of structure. General corrosion, pitting corrosion, intergranular corrosion, crevice corrosion and galvanic corrosion are the common forms observed. Among various aspects of corrosion, crevice corrosion (see Fig. 1) is a localized form of corrosion usually associated with a stagnant solution on the micro-environmental level. Such stagnant microenvironments tend to occur in crevices (shielded areas) such as those formed under gaskets, washers, fastener heads, surface deposits, disbonded coatings, lap joints and rivet holes. Therefore it is caused by damage to the aircraft structural performance of the major forms of damage. For this kind of corrosion, most previous works have been focused on chemical process and electric currents and potentials, but limited a precise understanding of the nature of the corrosion growth characteristics and the relationships with environmental factors. In order to investigate the mechanism of the metals crevice corrosion, and better understand how environmental factors influence the corrosion damage initiation and propagation on aircraft structure, cellular automaton (CA)² are mathematic algorithms which describe the discrete spatial and/or temporal evolution of complex physical systems applying local or global deterministic or probabilistic transformation rules to the cells.

In this paper, the corrosion model is based on local

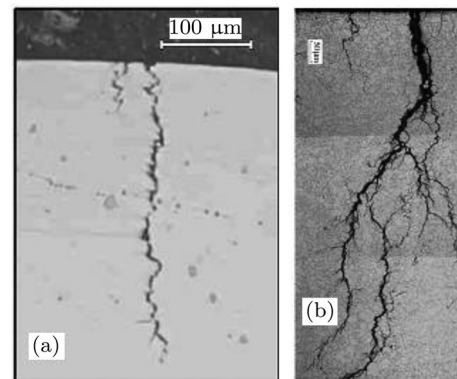


Fig. 1. The picture of crevice corrosion.

rules of evolution and it can be used to model the system at microcosmic or mesoscopic scales. The model is built in a finite lattice, where the system is discretized into regular network of sites, which are also called cells. The states of each cell are different at any given steps, and updating states of each cell occurs synchronously and is governed by a set of rules. As the state of each cell is updated, the macroscopic properties of the complex system due to the aggregate effect at the microcosmic or mesoscopic scales would be reflected and observed. Compared with other methods, the CA technique provides a simpler framework and it is more convenient and useful to describe the complex physical or chemical systems.

CA is a lattice model with discrete variables which are updated in discrete time steps according to a specified set of local rules. The dynamic behavior of systems containing many discrete elements with local interac-

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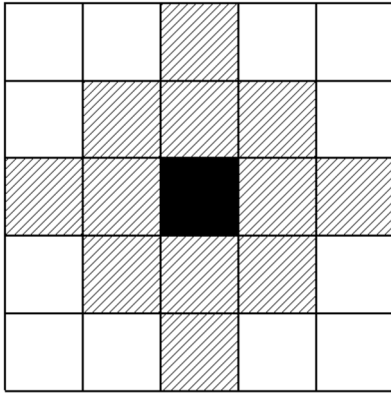


Fig. 2. Definition of neighborhood for the simulation model.

tions can be conveniently modeled in this way. Assume that the corrosion process is controlled by diffusion and the simulation focuses on the electrolyte/metal system interface.²

In this paper, four types of cells are defined in the model:² M indicates the metallic cell, which will be dissolved by corrosive cell, and when the M cell is subjected to corrosion, it changes into N cell; C indicates the corrosive cell; N indicates the vacancy (or non-corrosive cell), or else it can be seen as water molecule and other cells can occupy its site. The ratio of the number of C to the number of N is the concentration of the electrolyte. In order to simulate the diffusion process of the electrolyte, it is assumed that C can move up, down, left, right randomly in the cellular lattice.

Based on the diffusion and direction of the electrolyte cells, a CA neighborhood is employed which consists of a set of 12 nearest neighbors, a hybrid model of the von Neumann model and Moore model (see Fig. 2). In order to maintain the same concentration ratio C/N, periodical boundary³⁻⁵ condition is utilized.

The electrolyte/metal interface in the system is the object in the research. When metallic cell M is in contact with corrosive cell C, the chemical reaction may take place, and the metal may be dissolved.⁶ Assume that the corrosion process is controlled by diffusion and the corrosion only takes place at the electrolyte/metal interface.⁷ It is assumed that anodic and cathodic reactions appear at the same place, and the reactions do not change the acidity of the electrolyte.⁸ The metal dissolution is supposed to be taken place according to



The local rules of pit corrosion inferred from the above formulae are: when the neighbor of a metallic cell M is a corrosive cell C which is oriented towards the metallic cell M, the metallic cell M is dissolved and the site of the metallic cell M changes into an N cell after the reaction; when the neighbor of a metal cell M is a corrosive cell C, but the corrosive cell C is not oriented towards the metallic cell M, the metallic cell M remains a metal site; when the neighbor of a metallic

cell M is another metallic cell M, the metallic cell M remains a metal site.

For the diffusion process in the electrolyte system, all of the corrosive cells jump to their neighboring site randomly at each step. When a corrosive cell tries to jump to one of its neighboring sites, there are three cases should be mentioned:^{2,9}

(1) When the neighboring site is occupied by other cell, then the corrosive cell remains its current site and randomly chooses a direction to be oriented towards.

(2) When the neighbor site is null, but one or more other cells try to jump to the neighboring site as well, then the corrosive cell remains its current site and randomly chooses a direction to be oriented towards as well.

(3) When the neighboring cell is null, and no other cell tries to jump to the neighboring site, then the corrosive cell jumps to the neighboring site and randomly chooses a direction to be oriented towards.

In each step of the simulation process, the morphology of corrosion cells is determined, and we assume that the number of dissolved metal sites N_{cor} is a function of time, which represents the dissolution current. In the simulation process, we pay special attention to the role of the following parameters:¹⁰⁻¹²

(1) Electrolyte concentration c : the corrosive cell C and non-corrosive cell N are randomly distributed in the electrolyte and the ratio of the number of C to the number of N is the concentration of the electrolyte. The concentration of the electrolyte is changed by changing the ratio $c = C/(C+N)$, for example $c = 10/100$, $20/100$, $40/100$ and so on.

(2) Dissolution probability P : the P value changes from 0 to 1, which reflects the corrosion degree of corrosive cell: the larger value reflects the stronger corrosion.

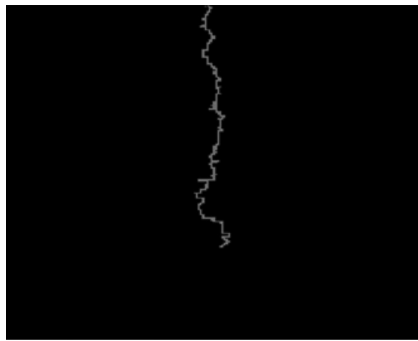
(3) Temperature T : T is the Celsius temperature. The cell moves faster in the electrolyte when the temperature is higher, so the speed of crevice growth is higher.

Considering the nature of cellular automaton, we find that all parameters are dimensionless.

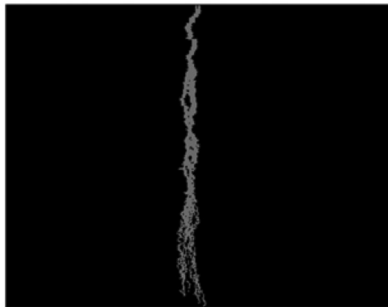
Figure 3 is the snapshots of a simulation at the same time steps ($t = 100$) for the damage evolution of crevice corrosion.

The phenomena obtained from the simulation are the same as that in the experiment of crevice corrosion, i.e. with the increase of corrosion time, the maximum depths of the crevice are deeper, the numbers of corrosion pit are added, the dimensions of the crevice are extended and the wider crevice are formed by the two or more crevice, the areas of the crevice are increased, the phenomena of interlacement between different crevice are more obvious, and the corrosion damage are more serious.

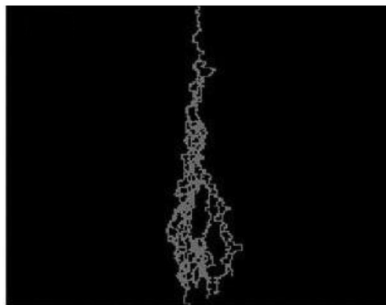
In Fig. 3, the damage evolution of crevice corrosion is simulated in different given corrosive environment. We assume that the number of dissolved metal sites represents the dissolution current. For different electrolyte concentrations, dissolution probabilities and temperature, the laws of the dissolution current with time are



(a) $c = 0.1, P = 0.3, T = 20$



(b) $c = 0.4, P = 0.3, T = 20$



(c) $c = 0.4, P = 0.9, T = 30$

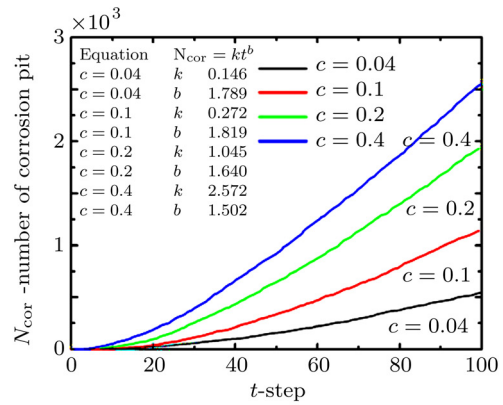
Fig. 3. Snapshots of a simulation at the same time steps for the damage evolution of crevice corrosion.

investigated and they obey the time power function: $N_{cor} = kt^b$ (the values of k and b change with the difference of corrosive conditions).

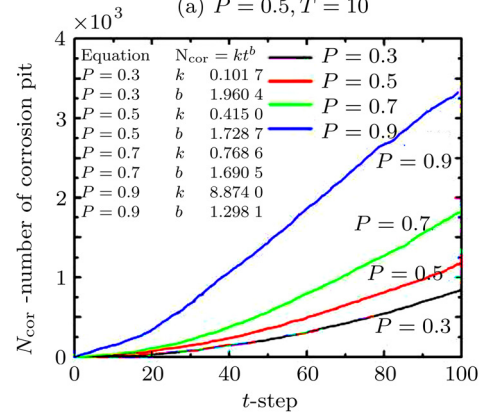
In Fig. 4(a), $P = 0.5, T = 10$, it shows the law of dissolution rate with time in different concentrations: the dissolution rate is more gentle with smaller concentration, when the concentration reaches a certain value, the law of the dissolution rate with time will obey the proportional function.

In Fig. 4(b), $c = 0.1, T = 10$, it shows the law of dissolution rate with time in different dissolution probability, when $P = 0.3$, the dissolution rate is very low, with the increase of dissolution probability, the dissolution rate speeds up significantly.

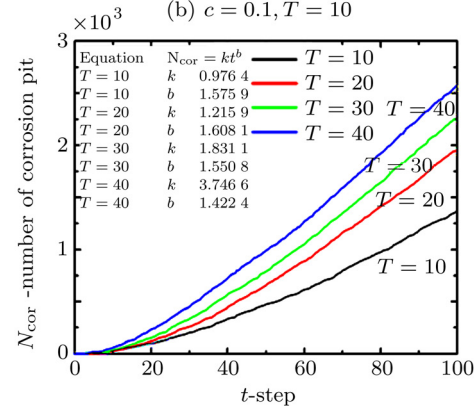
In Fig. 4(c), $c = 0.1, P = 0.5$, it shows the law of dissolution rate with time in different temperature, with the increase of temperature, dissolution rate with time



(a) $P = 0.5, T = 10$



(b) $c = 0.1, T = 10$



(c) $c = 0.1, P = 0.5$

Fig. 4. Effect of different electrolyte concentration c , dissolution probability P and temperature T on rate of dissolution N_{cor} .

becomes more and more approximate.

The CA method is effective for simulating corrosion damage of aircraft structure. It is an effective means to predict pre-corrosion test pieces of fatigue life and structural integrity of an effective approach. The main results can be summarized as follows:

The model for metal damage of crevice corrosion is proposed based on CA. Some simple local rules are defined to describe the elementary physicochemical processes, and the effects of the aggressive environment such as electrolyte concentration c , dissolution proba-

bility P , temperature T on the corrosion process are described by the number of corrosion cell.

The phenomena obtained from the simulation are the same as that in the experiment of crevice corrosion, and the results are in agreement with experimental data: the laws of dissolution current with time obey the time power function. All of these have proved that CA technique is a feasible and efficient approach to evaluate the corrosion damage and structural integrity.

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