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Failure Behavior Modeling : Towards a Better Characterization of Product Failures

Zhiguo Zeng*, Yunxia Chen, Rui Kang

School of Reliability and Systems Engineering, Beihang University, Weiminlou Building, 37# Haidian Dist., Beijing, P.R. China, 100191
zengzhiguo@dse.buaa.edu.cn

The characterization of failures is a crucial part of a prognostics and health management (PHM) program. Field failures of products often result from multiple failure mechanisms acting simultaneously. To better characterize them, it is necessary to understand both the failure mechanisms and the interactions among them. To achieve this aim, a framework for failure behavior modeling is presented in this paper. The framework builds the model from two aspects: modeling of individual failure mechanisms and of the interactions among them. For ease of the framework's application, the approaches for mechanism modeling and interaction modeling are discussed in details. Some commonly encountered failure mechanism models and frequently used interactive relationships are also presented with illustrative examples.

1. Introduction

The success of a Prognostics and Health Management (PHM) program relies heavily on detailed knowledge of failure processes. In order to gain such knowledge, numerous efforts have been devoted to the study of failure mechanisms, which are referred to as the physical or chemical processes leading to failures (Pecht and Dasgupta, 1995). Commonly encountered mechanisms have been thoroughly investigated so that effective mechanism models could be developed. In the 1990s, IEEE published a series of tutorials on Physics-of-Failures (PoF) (Dasgupta and Pecht, 1991; Diaz and Kang et al., 1995) and presented lots of failure mechanisms in a variety of areas. Since then, research and application of PoF have been greatly stimulated. Pecht and Dasgupta, (1995) introduced a general PoF methodology for electronics products which makes use of failure mechanism models to incorporate reliability into design processes. Other applications of failure mechanism models include reliability prediction (Goel and Graves, 2006), design of accelerated tests (Upadhyayula and Dasgupta, 1998), life predictions, etc.
The study of failure mechanisms is generally guided by the philosophy of Reductionism. Researchers first isolate the failure mechanism under investigation and then model the driven physical processes through either experiments or theoretical deductions. These methodologies have achieved great success in both academia and industries. However, field failures of actual products often result from the joint effects of multiple failure mechanisms. Thus, the interactions among potential mechanisms are important as well as individual mechanisms themselves. Being the focus of PoF researches, the failure mechanisms have received intensive research efforts and are relatively well understood. On the other hand, researches about interactions of mechanisms are limited. Most situations where multiple failure mechanisms exist are modelled as if the mechanisms do not interact with each other so that the weakest link model is applied (Pecht and Dasgupta, 1995). To cope with this problem, we will present a framework for failure behavior modeling with a focus on the interactions among multiple mechanisms.
The rest of the paper will be organized as follows. In section 2, the framework for failure behavior modeling is presented. The approaches for the modeling of mechanisms and interactions are discussed in detail in section 3 and 4, respectively. Some illustrative examples are also presented in these sections with respect to commonly encountered failure mechanisms and interactive relations. Finally, a short conclusion of this paper is drawn in section 5.

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2. From single to multiple mechanisms

2.1 Multiple mechanisms and synergistic effects

As reviewed before, most studies of physics-of-failure only dealt with situations where merely a single failure mechanism exists. For problems where several mechanisms operate simultaneously, assumptions about the independence among mechanisms are often made so that the weakest link model can be incorporated. However, in practice, actual products are usually subjected to the joint effects of multiple failure mechanisms where synergistic effects exist.

A typical example comes from the failure of pipes operated in marine applications. Malka and Nešić et al. (2007) and lots of other scholars have demonstrated that both the erosion caused by injected particles and the corrosion caused by chemical reactions have significant influence in the failure process of the pipes. Furthermore, their experimental results show that the presence of corrosions greatly affects the rate of erosions and vise versa (Malka and Nešić et al., 2007). For situations like these, the framework of failure mechanism modeling needs some improvements to incorporate the interactions among mechanisms.

2.2 A framework for failure behavior modeling

The aim of failure behavior modeling is to create a comprehensive description of failure regularities accounting for the interactions among failure mechanisms. Figure 1 shows a framework of failure behavior modeling. The modeling process starts with the identification of potential failure mechanisms and their interactive relationships. Then failure mechanisms are studies individually in order to establish appropriate mechanism models. Based on the built models, behavior modeling is performed to incorporate interactions among the mechanisms and finally arrive at a failure behavior model which is an adequate description of the failure processes under interacted failure mechanisms. Approaches to the two fundamental steps, the modeling of failure mechanisms and the modeling of their interactions will be discussed separately in the two succeeding sections.

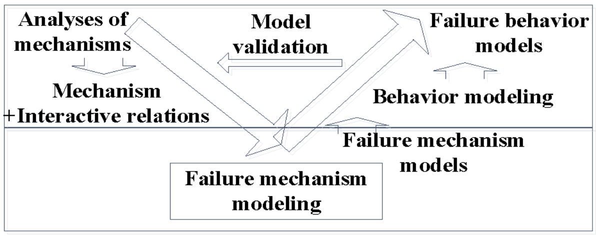

Fig 1: A framework for failure behavior modeling

3. Approaches to model failure mechanisms

Failure mechanisms are the physical or chemical processes which lead to failure (Pecht and Dasgupta, 1995). Failure mechanism model should be able to describe the relationship between time to failures and failure-inducing stresses. The modeling starts from an understanding and description of the physical processes. Generally there are three approaches for the modeling, namely the pure-empirical, semi-empirical and pure-theoretical approaches.

3.1 Pure-empirical approaches

The pure-empirical approach builds the model from the results of life tests under different stress conditions. The first step is to identify the process leading to failure and the stresses associated with the process. By designing experiments, life at different stress level can be determined. The relationships between stress levels and products' life are finally obtained by fitting the data to some empirical models.

The most common example of the pure-empirical approach is the stress-life approach for the prediction of fatigue life (Stephens and Fuchs, 2001). This approach is based on an experimentally determined curve (S-N curve) connecting stresses and the fatigue life. Operation profiles are analysed so that equivalent operated stresses could be determined and with the aid of the S-N curve, the fatigue life of the products under investigation can be predicted.

The pure-empirical model is built upon the results of failure tests and thus is the most accurate one among the three approaches. However, the high costs of the experiments severely limit the application of the approach. Moreover, the accuracy of the built model is strictly limited to the stress regions where experiments are undertaken. Extrapolations based on pure-empirical models should be made with great cautions.

3.2 Pure-theoretical approaches

Unlike pure-empirical approaches, the role of experiments is far less important in the pure-theoretical approaches, which only serve as validations of the built models. The approach models the failure processes directly from corresponding governing physical laws. Since the whole deduction processes are solely based on physical laws, the accuracy of the built models could be guaranteed.

One case of the approach is the calculation of material strengths based on first principles. In physics, a calculation is said to be from first principles, or ab initio, if it starts directly at the level of established laws of physics and does not make assumptions such as empirical model and fitting parameters. In (Liu, 2007), calculations of the strength of TiN are conducted from Schrödinger's equation within a set of approximations that do not include fitting the model to experimental data. The results show good consistency with those achieved from experiments.

Although pure-theoretical approaches are more accurate (compared with the semi-empirical one), the difficulties in finding governing physical laws for the failure processes limit the application of the approaches. Besides, even we can find the physical laws, the built models are often computational intractable (Van Krevelen and Te Nijenhuis, 2009). Often researchers have to make some appropriate assumptions to aid in the modeling and thus result in the third and most widely used approach: the semi-theoretical approach.

3.3 Semi-empirical approaches

Semi-empirical approaches are similar to the pure-theoretical approaches in the early stages. Both of them are started from the modeling of failure mechanisms through some fundamental physical laws. Unlike their ab initio counterparts, semi-theoretical approaches employ some empirical assumptions about the relationships between some micro-quantities and some macro-properties and thus greatly reduced the computational problems associated the built models. The example of the derivation of the failure mechanism model for electromigration in (McPherson, 2010) serves as a good illustration of the semi-empirical approach.

Electromigration is a common failure mechanism for interconnectors under high current intensity. It is caused primarily by the flux-divergence phenomenon with the movements of electrons. The flux-divergence will lead to either voids formations which will ultimately cause an open circuit failure or a build-up of metal ions which will result in a short circuit failure. The flux-divergence process can be modeled by Fick's Second Law, and starting from the law, a series of deductions based on physical laws and principles are conducted which leads to the model in equation (1), where f_{crit} is a threshold value, $N(t)$ is the number of particles of a given time and $\langle \bullet \rangle$ stands for averaging against time.

$$TF = \frac{\ln(1/f_{crit})}{\left\langle \int \vec{J}(x,t) d\vec{A} / N(t) \right\rangle}. \tag{1}$$

The $J(x,t)$ in equation (1) can be determined from Fick relations, as shown in equation (2), where μ is the mobility constant, D is the diffusion constant and F is the external driven forces exerted on the particles.

$$\vec{J}(x,t) = \mu\rho(x,t)F - D\frac{\partial\rho(x,t)}{\partial x}. \tag{2}$$

The combination of equation (1) and (2) could give a prediction of electromigration failures. However, the determination of F in equation (2) and the calculation of the average value in equation (1) from physical laws are complex and sometimes computational intractable. In most cases, the following simplification assumptions are employed: 1. The direction of particle flux is perpendicular to the area $\vec{A}$ and the diffusion constant D in equation (2) is small; and 2. There is a relationship between the driven force F in equation (2) and the current density J_e, which is $F \propto J_e^n$. Under these assumptions, the failure mechanism model becomes

$$TF = A_0 J_e^{-n} \exp\{\frac{Q}{K_B T}\}. \tag{3}$$

Since Eq (3) is built under several assumptions for simplification, the built model should be justified through experiments. This is the last yet most important part of the semi-empirical modeling approach.

Experiments are designed according to the built models and the result of the experiments will both validate and calibrate the model. As to our example on electromigration, lots of experimental studies have confirmed the model in Eq (3) (McPherson, 2010).

4. Interactions between failure mechanisms

In the study of failure mechanism, mechanisms are isolated and investigated individually. However, actual products are subjected to multiple failure mechanisms and the interactions among the mechanisms play a crucial role in the formation of failures. Thus, in order to better characterize failures, the interactions should also be accounted for.

4.1 Mechanism independence

Two or more mechanisms are independent when the presence of one mechanism has little or no influence on the others. If the mechanisms are independent, the interactions among them can be modeled by the weakest link model. In this model, failures are triggered by the mechanism whose predicted time to failure is the shortest, as shown in Eq (4).

$$TF = \min_{i=1}^{n} TF_n \tag{4}$$

An example of the interactions of independent failure mechanisms is the failure of composite plies (Whiteside and Pinho et al., 2012). There are three failure mechanisms for the composite ply and each of them results in a specific failure mode. The mechanisms include fiber tensile (f_{ft}), matrix failure (f_{mat}) and fiber kinking/splitting ($f_{kink/split}$) and models describing them are presented in Eq (5) to (7).

1. Fiber tensile

$$f_{ft} = \left(\frac{\sigma_1}{\sigma_L^+} \right)^2 \geq 1. \tag{5}$$

where σ_1 is the main stress and σ_L^+ is the tensile strength in the longitudinal direction parallel to the fibers.

2. Matrix failure

$$f_{mat} = \left(\frac{\tau_{23}^{\phi_0}}{\tau_T - \mu_T \sigma_n^{\phi_0}} + \frac{\tau_{12}^{\phi_0}}{\tau_L - \mu_L \sigma_n^{\phi_0}} + \frac{\sigma_{n+}^{\phi_0}}{\sigma_T^+} \right) \geq 1. \tag{6}$$

where $\tau_{23}^{\phi_0}, \tau_{12}^{\phi_0}, \sigma_n^{\phi_0}$ is the components of stresses in the specific directions, $\tau_T, \tau_L, \sigma_T^+$ are the corresponding strengths and μ_L, μ_T are coefficient of frictions in the specific directions.

3. Fiber kinking/splitting

$$f_{kink} = f_{split} = \left(\frac{\tau_{23}^{m_0}}{\tau_T - \mu_T \sigma_2^{m_0}} \right)^2 + \left(\frac{\tau_{12}^{m_0}}{\tau_T - \mu_T \sigma_2^{m_0}} \right)^2 + \left(\frac{\sigma_{2+}^{m_0}}{\sigma_T^+} \right). \tag{7}$$

The meaning of each parameter is consistent with those in equation (5) and (7). In an actual composite ply, the three mechanisms are independent from each other and the weakest link model can be used to model the interactions among them, as shown in equation (8)

$$f_{PB} = \max\left(f_{ft}, f_{max}, f_{kink}, f_{split} \right) \geq 1. \tag{8}$$

4.2 Velocity summation

In many cases, failures are associated with and can be represented by one or several measurable quantities. Thus, the failure processes are the processes in which the variation of these quantities takes places. Velocity summation is a kind of model for the interactions among mechanisms where all of them contribute to the same quantity directly connected to failures. If the premises are valid, the total rate of variation can be obtained from the summation of those of each failure mechanism, as shown in equation (9).

$$\frac{dp}{dt}=\sum_{i=1}^{n}\frac{dp_i}{dt}, \tag{9}$$

where dp/dt is the variation rate resulting from all mechanisms and $dp_i/dt, i=1,2,\cdots,n$ are the variation rates resulting from each individual failure mechanism.

A typical example of this kind of interaction is the modeling of time-dependent dielectric breakdown (TDDB) in (McPherson, 2010). TDDB can be modeled by two mechanism models, the E-model (equation (10)) and the 1/E-model (equation (11)).

$$TF=A_0\exp\{-\gamma E_{ox}\}\exp\left\{\frac{Q}{K_B T}\right\}. \tag{10}$$

$$TF=\tau_0(T)\exp\left\{\frac{G(T)}{E_{ox}}\right\}. \tag{11}$$

Since the two mechanisms exist simultaneously, the velocity summation principle is employed to model the time to failure of TDDB, as shown in Eq (12),

$$k=k_E+k_{1/E}, \tag{12}$$

where $k, k_E, k_{1/E}$ are the rate constant of the whole process, the E-model and the 1/E-model, respectively. If the rate of each model is a constant, equation (13) leads to

$$TF=\frac{TF_E \cdot TF_{1/E}}{TF_E+TF_{1/E}}. \tag{13}$$

4.3 Damage accumulation

Damage accumulation rules are widely applied to the model the interactions of failure mechanisms. The fundamental assumptions behind these rules are the operation of products produces damages to the products and failures are caused by the accumulation of damages. The most widely applied form of damage accumulation is Miner's rule. Originated from fatigue life predictions, the rule assumes that the damage of each cycle can be decided from,

$$D_i=\frac{t_i}{T_i}, \tag{14}$$

where t_i is the duration of each cycle and T_i is the expected time to failure of the specific failure mechanism. The damages accumulated from individual mechanisms and the repetition of operation cycles. When the accumulated damage reaches one, failures of the products are triggered.

An example of applying damage accumulation rules to model the interactions of mechanisms is the failures resulting from fatigue and creep (Pulido, 2012). The time to failure (in cycles) of products subjected both fatigue and creep mechanisms can be decided from

$$N=\left(\frac{1}{N_f}+\frac{\tau}{T_C}\right). \tag{15}$$

where the two components in the brackets are the damage from fatigue and creep, respectively.

4.4 Mechanism coupling

The previously discussed interactive relations are some special cases in the variety of actual relations. It is absolutely impossible that the three relationships can cover all kinds of interactions in practice. In lots of other situations, mechanisms are coupled together, which means that the presence of one mechanism will exert influence on the others. In these situations, it is hard to obtain general approaches to model the synergistic effects among the coupled mechanisms and an ad hoc analysis should be performed for each case. To start with, one has to understand the way in which mechanisms are coupled. Often the couplings are caused by the change of driving conditions of one mechanism due to the affections from other mechanisms. For example, the wear of materials will deteriorate their strengths and in turn affect the fatigue life under cyclic loads. Once the coupling mechanism is understood, appropriate models can be derived accordingly.

5. Conclusions

In this paper, a problem with existed failure mechanism modeling methodologies about their inability to incorporate the interactions of mechanisms into the models is raised. In the face of this problem, a framework for failure behavior modeling is presented in this paper. Taking the interactions of mechanisms into consideration, the framework can yield a more a comprehensive model for failure regularities. The two fundamental steps in the framework, modeling of failure mechanisms and modeling of interactive relations are also discussed in details. Three commonly utilized approaches to failure mechanism modeling, the pure-empirical, the pure-theoretical and the semi-empirical approaches are presented with illustrative examples. Four frequently encountered interactive relations are also reviewed and illustrated with examples.

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