Comparison of Models of Stress Relaxation in Failure Analysis for Connectors under Long-term Storage

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Abstract. Reliability requirements of the system equipment under long-term storage are put forward especially for the military products, so that the connectors in the equipment also need long-term storage life correspondingly. In this paper, the effects of stress relaxation of the elastic components on electrical contact of the connectors in long-term storage process were studied from the failure mechanism and degradation models. A wire spring connector was taken as an example to discuss the life prediction method for electrical contacts of the connectors based on stress relaxation degradation under long-term storage.

1. Introduction
The electrical connector is an interface between the conductive components in an equipment and those in other equipment. Its function is to transfer electrical energy or signal from one system to another. Electrical connectors are scattered in every parts of the system. Each connector contains several pairs or even hundreds of pairs of electrical contacts. According to statistics, 28% of the current system failures are caused by the failure of electrical connectors [1]. Most connectors under storage conditions are exposed to the air and are subject to various environmental factors such as temperature, humidity, atmospheric corrosion, etc. It involves failure mechanism such as stress relaxation of elastic materials, diffusion of the base material, and pore corrosion. The distribution of micro-pores on gold plating is discrete resulting in a relatively small probability of pore corrosion at small contact zones, especially for multiple pairs of contacts in parallel, so the effect of pore corrosion on electrical contact properties is ignored here. Most connector materials are plated with an intermediate layer, such as nickel, between the copper substrate and the gold plating on surface, which hinders the diffusion of the copper to the surface coating. Therefore, the process of electrical contact failure caused by the diffusion of the substrate material is very slow, which can also be neglected. Then, the failure mechanism of stress relaxation for elastic materials needs to be analysed and discussed. In this paper, three degradation models of stress relaxation were compared, the storage life of the wire spring connector was primarily estimated based on the accelerated experiments.
2. Failure analysis of stress relaxation of connectors

2.1. Mechanism and main influencing factors of stress relaxation
Stress relaxation is the contact pressure decreases with time under constant deformation. The process of stress relaxation is usually divided into two stages [2]. From a microscopic perspective, at first stage, the movable dislocation is remarkable while the driving force is high [3], so the speed of stress relaxation is fast. At second stage, the stress relaxation rate is small, because the dislocation and impurity atoms interact with the second phase particles, causing dislocations to proliferate, thus impeding dislocation movement.

The main factors affecting material stress relaxation are temperature, initial applied stress and material compositions. Temperature has the greatest effect on stress relaxation. Increasing temperature will change the microstructure of the material then will accelerate the loss of contact pressure [4], having an accelerating effect on two stages of stress relaxation. Stress relaxation is also affected by the size of the initial applied load. The more rapidly stress relaxation changes, the higher contact pressure is applied to the components. The relaxation rate is almost constant when the initial stress is between 30% and 90% of the yield strength at 0.2% residual strain [5]. After comparing the stress relaxation data of copper and copper alloys for electrical connectors, it was found that the combination of different alloying elements with pure copper increases its resistance to relaxation and its magnitude of anti-relaxation can vary depending on the type and amount of alloying elements added [5].

2.2. Model of stress relaxation of elastic materials
The common stress relaxation models are divided into empirical model and failure physical model, with time as the independent variable and residual stress as the dependent variable. Among the three models described below, the model a is the empirical model of stress relaxation and Larson-Miller parameter after extensive relaxation tests; the model b is a failure physics model based on the derivation of Arrhenius behaviour; based on the material parameters (E, η), a Maxwell linear elastic-viscous body physical model is proposed in the model c.

a. Empirical model of stress relaxation and Larson-Miller parameters
Stress relaxation can be characterized by permanent deformation or stress variation, when stress relaxation is characterized by deformation, the expression is [6]:

\[ \log \left( \frac{X}{X_0} \right) = aT \left( \log t + C \right) + b \]  
(1)

Where: X is the permanent deformation at time, \( X_0 \) is the initial deformation, T is the absolute temperature, t is the time, a and b are the constants to be determined, and the range of constant C is 16-20. At constant temperature, it can be further rewritten as:

\[ \log \left( \frac{X}{X_0} \right) = A \log t + B \]  
(2)

In the formula, A and B are parameters related to temperature, which can be obtained by the least squares method. When the stress relaxation quantity is characterized by residual stress, the expression is:

\[ \log \left( \frac{\sigma_0 - \sigma_t}{\sigma_0} \right) = A \log t + B \]  
(3)

Further rewritten as:
\[ \lg \left( \frac{\sigma}{\sigma_0} \right) = A' \lg t + B' \]  

(4)

Therefore, (2) (3) (4) can be considered as completely equivalent. The logarithm of relaxation amount is linearly correlated with the logarithm of time through the test data, regardless of being characterized by deformation or residual stress representation. The contact reed material of the test is divided into beryllium bronze and tin bronze strip [6], the \( \frac{X}{X_0} \)-\( \lg t \), which is fitted at four temperatures, is linearly related and is coincide with test data points.

b. The model of stress relaxation based on Arrhenius behaviour [7]:
\[ t_1 = A e^\frac{Q}{kT} \left[ e^{\frac{1}{\beta}(1-\frac{\sigma_t}{\sigma_0})} \right] \]  

(5)

\( t_1 \) : time (in seconds) ; \( Q \) : activation energy ; \( k \) : Boltzman constant \( (1.38 \times 10^{-23} \text{J/K}) \) ; \( T \) : absolute temperature ; \( A, \beta \) : temperature-dependent coefficient.

\[ \frac{\sigma_t}{\sigma_0} = -\beta \ln t_1 + \beta \ln A + \beta \left( \frac{Q}{kT} \right) + 1 \]

At a constant temperature, can be further converted to:
\[ \sigma_t = A_0 \lg t + A_1 \]  

(6)

The model shows that at a certain temperature, the residual stress is linear with the logarithm of time.

Whitley used the Bell Telephone Laboratories (BTL) to develop a method of determining the post-heat age relaxation of the hoop stress in copper wire wrapped around a nickel-silver [7].

c. MAXWELL linear elastic-viscous body model

Imagine the material’s hysteresis elasticity and viscous behaviour as a combination of linear elasticity (following Hooke’s law of elasticity) and linear viscosity (Newton’s liquid damping cylinder) behaviour [8]:

\[ \sigma = E \cdot \varepsilon_e \text{ and } \sigma = \eta \cdot \varepsilon_\eta \]

Where \( \sigma \) is the normal stress, \( \varepsilon_e \) is elastic strain, \( \eta \) is the viscosity, \( \varepsilon_\eta \) is ideal line viscous strain rate.

![Figure 1. MAXWELL model for stress relaxation of beryllium bronze material](image)

Based on the definition of stress relaxation, there is:
\[ \dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_\eta = 0 \]

Substitute the stress-strain relationship:
\[ E \dot{\varepsilon}_e = \sigma - \frac{E}{\eta} \dot{\varepsilon}_\eta = 0 \]

where \( \dot{\varepsilon} \) is total strain rate, \( \dot{\varepsilon}_e \) is ideal line elastic strain rate, \( \dot{\sigma} \) is the stress rate, \( E \) is the ideal elastic modulus volume.
Let \( t_R = \frac{\eta}{E} \), which is called the time factor (time-independent, temperature dependent), then

\[
\frac{d\sigma}{\sigma} = -\frac{dt}{t_R}
\]

After the integration: \( \ln \sigma = -\frac{t}{t_R} + C_0 \), \( C_0 \) is constant.

Consider when \( t=0 \), \( \sigma = \sigma_0 \), \( \sigma_0 = E\varepsilon_0 \), then: \( C_0=\ln\sigma_0 \),

\[
\sigma = \sigma_0 \cdot \exp\left(-\frac{t}{t_R}\right)
\]

\[
\ln\frac{\sigma}{\sigma_0} = -\frac{1}{t_R} \cdot t
\]

where: \( \sigma_0 \) is the initial stress, \( t \) is the stress relaxation time. Establish the relationship between residual stress and time.

Suppose: \( \eta=\eta_0 \cdot \exp\left(-\frac{Q}{KT}\right) \), then

\[
\ln\frac{\sigma}{\sigma_0} = -\frac{E}{\eta_0} \cdot \exp\left(Q/KT\right) \cdot t
\]

At a certain temperature, supposing \( \frac{E}{\eta_0} \cdot \exp\left(Q/KT\right)=C \), then \( C \) is constant, So the above formula becomes:

\[
\ln\sigma_t = \ln\sigma_0 - Ct
\]

The model expresses the stress relaxation behaviour of materials related to time and temperature through mechanical model. It is verified that the curve of bending stress relaxation of beryllium bronze strip accords well with the experimental data points, and the error is no more than 5%.

2.3. Comparison of test data fitting

A high temperature acceleration experiment was done on a wire spring connector of a beryllium bronze material, and the loss of contact pressure was characterized by separating force. From \( \sigma = F/S \), where \( F \) is contact pressure, \( S \) is the contact area. It is assumed that in the process of stress relaxation, the area \( S \) is unchanged, and the residual stress \( \sigma_t \) in three models can be replaced with \( F \). The test data were fitted under 144°C in three models, as shown in table 1.

| No. of Models | Type of models | Model(At 144°C) | R-sqre |
|---------------|----------------|----------------|--------|
| a             | Empirical formula: \( \lg \left( \frac{F_t}{F_0} \right) = -0.2332\lg t -0.063 \) | 0.973 |
| b             | Based on Arrhenius behaviour: \( \frac{F_t}{F_0} = -0.2418\lg t + 0.759 \)  | 0.953 |
| c             | Based on linear elasticity -viscous body: \( \ln F_t = -0.006216t + 3.868 \) | 0.705 |

3. DISCUSSION

3.1. Analysis of the model of stress relaxation

It can be seen from the experimental data that under the condition of high temperature, the fitting of model a is the highest. The Model b is the least and the model c has the worst fitting result. Obviously,
model c is not suitable for this type of wire spring connector. Because the change of contact force under high temperature is remarkable, the decrease of contact force is not obvious when the temperature is low. The closer to the room temperature is, the more difficult to test. Therefore, the empirical formula fitted from a large amount of experimental data does not guarantee a high degree of reliability when extended to room temperature. Model b follows the Arrhenius behaviour and takes the parameter temperature and the initial stress mainly affecting stress relaxation of the connector into consideration. Theoretical deduction based on the failure physics makes it more rational for the prediction of stress relaxation. In summary, it is considered that model b has the best generality for predicting the stress relaxation behaviour of connectors.

3.2. Effect of stress relaxation on electrical contact properties
Connectors require low and stable contact resistance in applications. Thus, the contact resistance is used here as a degradation parameter for long-term storage of the connector to evaluate the storage life. For the convenience of discussion, if the two contact elements are the same material, the contact resistance expression on a contact pair is [9]:

$$R = R_c + R_f = \frac{\rho}{2} \sqrt{\frac{H}{F}} + \frac{\sigma_f H}{F}$$  \hspace{1cm} (9)

Where $R_c$, $R_f$ respectively represent the constriction resistance and the film resistance; $\rho$ is resistivity of the conductor material; $H$ is metal material's hard; $F$ is contact pressure; $\sigma_f$ is tunnel resistivity of the film.

When only the effect of stress relaxation on the increment of contact resistance is considered, the (9) is converted into:

$$\Delta R = \rho \sqrt{\frac{H}{2}} \left( \frac{1}{\sqrt{F_t}} - \frac{1}{\sqrt{F_0}} \right) + \sigma_f H \left( \frac{1}{\sqrt{F_t}} - \frac{1}{\sqrt{F_0}} \right)$$

If the area S is invariant during stress relaxation, contact force F replaces equation (6) where residual stress $\sigma_t$, to logarithmic after both sides:

$$\Delta R = \left( \frac{\rho \sqrt{H}}{2} + \sigma_f H \right) \left( \frac{1}{\sqrt{F_0}} \right) \left( \frac{1}{\sqrt{A_0 \log t + A_1}} \right) - 1$$

Let $K = \left( \frac{\rho \sqrt{H}}{2} + \sigma_f H \right) \sqrt{F_0}$, the above formula can be rewritten as:

$$\left( \frac{1}{\Delta R K + 1} \right)^2 = A_0 \log t + A_1$$  \hspace{1cm} (10)

At 144 °C, the parameter $A_0$, $A_1$ in equation (6) can be fitted by the test data, which is 0.2418 and 0.759 respectively. Substituting equation (10) into the experimental data of the contact resistance increment and time ($\Delta R$-t), the constant K can be fitted to 0.7385. After finishing the following formula, then:

$$\left( \frac{1}{\Delta R K} \right)^2 = -0.2418 \log t + 0.759$$  \hspace{1cm} (11)
The experimental data at 144 °C can be seen that the stress relaxation is divided into two stages, achieving a stable state after 16h, that is. Calculated by (11) formula, the contact resistance increases by 34.1% when the stress relaxation reaches stable state. Similarly, the increase in contact resistance at which the connector reaches the maximum amount of stress relaxation at different temperatures can thus be estimated.

3.3. Prediction and analysis of stress relaxation life
The following deduction is based on Model b for life prediction analysis. By Arrhenius theory, when the stress relaxation rate reaches a certain value, each test temperature and time follows the following relationship [10]:

\[
\frac{1}{t_f} = Ae^{-\frac{Q}{RT}}
\]

Take the logarithm on both sides and arrange it: \( \ln t_f = \frac{Q}{R} \cdot \frac{1}{T} + (\ln 1 - \ln A) \)

that is:

\[
\ln t_f = \frac{Q}{R} \cdot \frac{1}{T} + B \quad (12)
\]

By the equation (12), the logarithm of time has a linear relationship with the reciprocal of temperature. Through the acceleration experiments of different temperatures, the model is fitted first, and then according to the method in section 3.2, the corresponding time is obtained when the contact resistance increment reaches the threshold value. The linear expression of \( \ln t_f \cdot \frac{1}{T} \) can be obtained by fitting the relationship between temperature gradient and corresponding time according to (12). Thus, the life prediction of the elastic element on contact point of the connector due to stress relaxation is realized.

4. Conclusion
In this paper, the stress relaxation is analysed from mechanism and influencing factors, and the existing stress relaxation degradation models are summarized and compared. A wire spring connector with beryllium bronze material was tested using a series of high-temperature accelerated experimental data fitting in accordance with three types of degradation models. It was found that the empirical formula had the best fitting degree and the fitting effect of linear elastic-viscous body model was the worst. However, from the perspective of failure mechanism, it is considered that the model following Arrhenius behaviour is more suitable for describing the stress relaxation behaviour of elastic elements and has better generality under different temperature gradients. At 144°C, the contact resistance of the connector is increased by 34.1% when the stress relaxation reaches the stable value. Using high-temperature accelerated test can predict the contact resistance of the connector rises to a certain threshold value. Then the relationship between the different temperature and the corresponding failure time is obtained by fitting, and the extrapolation to room temperature can predict the storage life of the contact resistance due to stress relaxation under long-term storage condition of the connector.

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References:
[1] Li S D, Pan J and Chen W H 2010 J. Electromechanical Components. 29 pp 53-56
[2] Xiao X P and Liu R Q 2015 J. Materials Review. 29 pp 148-151
[3] Wang D J, Zhang W F and Fang X T 2013 J. Advanced Materials Research. 750-752 pp 675-678
[4] Milenko B and Valery V K 2007 Electrical Contacts Fundamentals, Applications and Technology (Boca Raton: CRC Press) pp 2-7
[5] Kenneth W H 1982 Proc. Fifteenth Annual Connectors and Interconnection Technology Symp. (Philadelphia) 11 pp 325-336
[6] Li M H 1985 J. Electromechanical Components.1 pp 52-58
[7] Beach K L and Pascucci V C 2000 Proc. of the Forty-Sixth IEEE Holm conf. (Chicago) pp 1-17
[8] Zhang X M and Mao X P 2001 J. The Chinese Journal of Nonferrous Metals. 6 pp 988-992
[9] Wang S J 2017 J. Journal of Mechanical Engineering. 10 pp 180-186
[10] Fox A 1980 J. Journal of Testing and Evaluation. 3 pp 119-126