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Machine learning-based prediction of remaining useful lifetime for solder joints based on real mission profile data

Vorhersage der Restnutzungsdauer von Lötverbindungen mit Hilfe maschinellen Lernens unter Verwendung realer Einsatzdaten

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Abstract: In an increasingly digitalized world, electronic systems are central to the operation of essential services. Ensuring the reliability of these systems is crucial, particularly in safety-critical applications where failures can have serious consequences. On circuit boards, solder joints are one of the key interconnection components whose degradation over time poses a significant challenge for system longevity. To address this, the Prognostic and Health Monitoring (PHM) domain has emerged as a promising solution framework to enable early detection of potential failures and support condition-based maintenance strategies. In this article, we present a methodology to estimate remaining useful lifetime (RUL) of solder joints under field operation. A light rail vehicle (tram) was equipped with sensors to measure mission profile loads (mainly temperature data) near the critical electronic components. In parallel, a finite element-based digital twin model of a solder joint was developed to generate a training data set. Then, a multilayer perceptron (MLP) was used to correlate the temperature characteristics with fatigue evolution in the solder joint. The MLP was able to predict fatigue increments with good accuracy which enables the estimation of further lifetime consumption. The major challenge with insufficient loading data, especially operational mission profile data, was addressed by supplementary synthetic data. Finally, the lifetime modeling method is presented in this article. Overall, this work provides a solution to estimate RUL of solder joints under mission profile loads, suitable for a portable inline PHM framework.

Keywords: Solder joints; PHM; RUL; digital twin; lifetime modeling

Zusammenfassung: In einer zunehmend digitalisierten Welt sind elektronische Systeme von zentraler Bedeutung für den Betrieb wichtiger Dienste und Anwendungen. Die Gewährleistung der Zuverlässigkeit dieser Systeme ist von entscheidender Bedeutung, insbesondere bei sicherheitskritischen Anwendungen, bei denen Ausfälle schwerwiegende Folgen haben können. Auf Leiterplatten sind die Lötstellen eine der wichtigsten Verbindungskomponenten, deren Ermüdung im Laufe der Zeit eine erhebliche Herausforderung für die Langlebigkeit des Systems darstellt. Daher hat sich der Bereich Prognostic and Health Monitoring (PHM) als vielversprechender Lösungsrahmen herauskristallisiert, der eine frühzeitige Erkennung potenzieller Ausfälle ermöglicht und zustandsorientierte Wartungsstrategien unterstützt. In diesem Artikel stellen wir eine Methode zur Abschätzung der verbleibenden Nutzungsdauer (remaining useful lifetime - RUL) von Lötstellen im Feldbetrieb vor. Eine Straßenbahn wurde mit Sensoren ausgestattet, um die Belastungen im Einsatzprofil in der Nähe der kritischen Komponenten zu messen (vorwiegend Temperaturdaten). Ein auf finiten Elementen basierendes Modell eines digitalen Zwillings der Lötstelle wurde entwickelt, um einen Trainingsdatensatz zu erzeugen. Somit konnte ein Mehrlagiges Perzeptron (MLP) eingesetzt werden, um Temperaturinformationen mit der Ermüdungsentwicklung im Lotkontakt zu korrelieren. Das MLP war in der Lage, die Ermüdungszunahme mit guter Genauigkeit vorherzusagen, was eine weitere Abschätzung des Lebensdauerverbrauchs ermöglicht. Das große Problem der unzureichenden Belastungsdaten, insbesondere der Daten zum Einsatzprofil, wurde durch ergänzende synthetische

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Daten gelöst. Darüber hinaus wird in diesem Artikel eine Methode zur Modellierung der Lebensdauer vorgestellt. Insgesamt bietet diese Arbeit eine Lösung zur Abschätzung der RUL von Lötstellen unter Einsatzprofilbelastungen, die sich für ein portables Inline-PHM-System eignet.

Schlagwörter: Lötverbindungen; PHM; RUL; digitaler Zwilling; Lebensdauermodellierung

1 Introduction

Reliance on modern electronic systems has never been higher. In majority, the systems are critical to the product functionality and consequently, reliability has shifted from being a key objective to a mandatory compliance criterion. Due to rapid modernization across all domains, design cycles are getting reduced which affects the electronic systems as well. They are also becoming smaller, more complex and susceptible to reliability issues during their life cycle. The PHM discipline proactively addresses the reliability and maintenance-related activities based on the continuous monitoring and by providing advance warning on failures [1]. However, to successfully detect and classify a failure during operation, significant background knowledge on failure mechanisms and ultimate lifetime needs to be developed.

Solder joints are one of the most important and widely used interconnection technologies [2]. Damaged solder joint limits the mechanical and electrical connectivity. They are typically made of alloys and have a different thermal expansion behaviour compared to the other materials of printed circuit boards, copper pads, die, chip and other metalizations. It is well established that solder experiences thermomechanical fatigue, dominated by creep, even at normal operating temperature. This fatigue information can be used to set up accurate lifetime models for evaluating the life consumption due to temperature exposure. Both of these key challenges are addressed in this article: solder fatigue prediction and lifetime modeling for RUL evaluation.

2 Solder fatigue prediction

The primary goal is to estimate RUL of solder joints under mission profile loads. In order to do that, we require accurate lifetime models of solder joints (see Section 3). Typically, they are based on several factors among which failure mechanism is the critical aspect. Solder joints suffer the most from thermomechanical fatigue, dominated by creep over prolonged, dynamic temperature cycles. Therefore, it is essential to develop a method to correlate temperature loads to fatigue increments. With the further implementation for an inline PHM framework as an objective, data-driven ML-based prediction models are well suited and were explored intensively in the recent years [3].

In this section, we want to summarize the methodology developed and reported in [4]. A schematic of the approach is provided in Fig. 1. It is critical to understand the loading characteristics that cause the fatigue in solder joints. Often, such a loading data set is limited and can only be generated via extensive, continuous measurements in test vehicles. Therefore, an addition of synthetic data was considered here. Previous studies have confirmed, that synthetic data help not only in extending the value ranges but are also obtained much faster [5, 6].

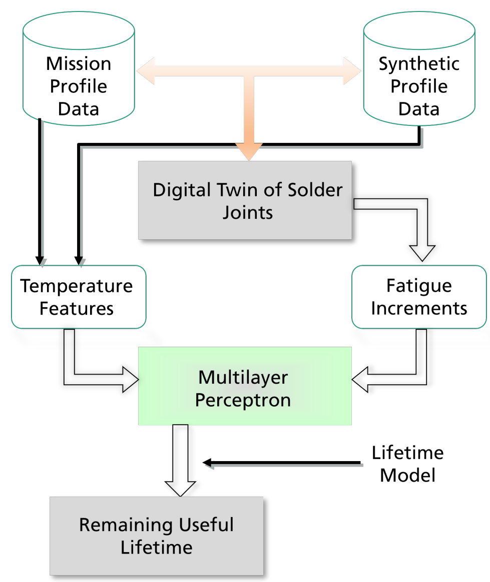

Fig. 1: RUL estimation methodology for solder fatigue.

A digital twin FE model was used to produce the necessary fatigue increments under synthetic temperature profile data and the limited real mission profile. As reported in [7], full temperature-time profiles are transformed into half-cycle features. This constitutes a training data set with temperature half-cycle values as the input features and corresponding fatigue increments as the target features. In the next step, an MLP model was trained, which can predict fatigue increment for unknown temperature fluctuations. With a suitable lifetime model, lifetime consumption or remaining life was evaluated. Such, continuous evaluation of RUL during the operation can be used for failure anticipation and maintenance planning.

2.1 Temperature loading data

This work is tailored for a specific application of a transportation vehicle, a street tram. The power converter assembly in the trams experiences major temperature fluctuations during operation; therefore, the electronic failure potential is also high. However, continuous monitoring of such data is equally costly and often overlooked. For this work, limited mission profiles were directly measured at the location of interest in the power converter assembly. In addition, the authors reported on an ML-based virtual sensing model to increase the database in [4]. It helped to increase the mission profile database. Figure 2 shows the sensor placement on the electronic boards of the power converter assembly. During the normal operation of the tram, the temperature fluctuations were measured and sent to the storage location via long term evolution (LTE)-technology.

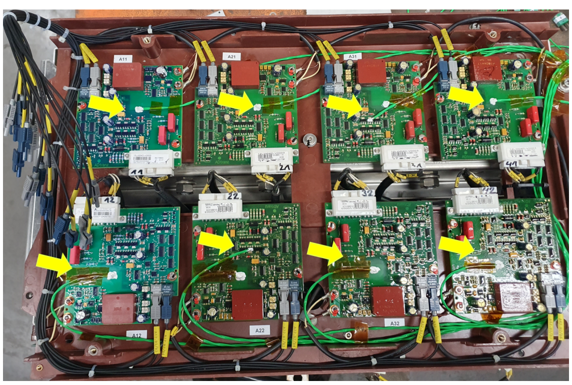

Fig. 2: Sensor placement for the mission profile data acquisition in the power converter assembly of a tram [4].

In parallel, a synthetic temperature profile was generated. The main purpose was to enhance the value ranges and also improve the overall data distribution. It was created by accumulating various temperature half-cycles of different characteristics: temperature range, gradient, step and dwell times. In that way, the overall distribution is suited for all possible scenarios which might occur in a tram at different conditions, weather, etc.

In the next step, a finite element-based digital twin of a solder joint was created. A surface mounted chip resistor, which is soldered onto a printed circuit board (PCB), was used as test example. The geometry specifications are corresponding to a standard CR1206 chip resistor. Details on the FE model can be taken from [4, 7]. With this model, fatigue evolution in the solder joint standoff region was evaluated under synthetic temperature profile and mission profile data.

2.2 Multilayer perceptron

An MLP is a neural network with input, output and hidden layers neurons densely connected. It is capable of understanding non-linear relationships between the input and target features. In this work, two hidden layers, with 256 and 128 neurons respectively, were used with Leaky-ReLU as their activation function. Adam optimization was employed during the training procedures. The model was capable of learning how different temperature half-cycles lead to fatigue increments. The coefficient of determination (R^2) for predictions with an unseen test data set was 0.93. For more practical understanding, we also accumulated all the individual predictions over time and compared it to simulations as shown in Fig. 3. It was noticed that the averaged error between the model predictions and the simulation was less than 5 %, which increases the confidence in the fatigue prediction model.

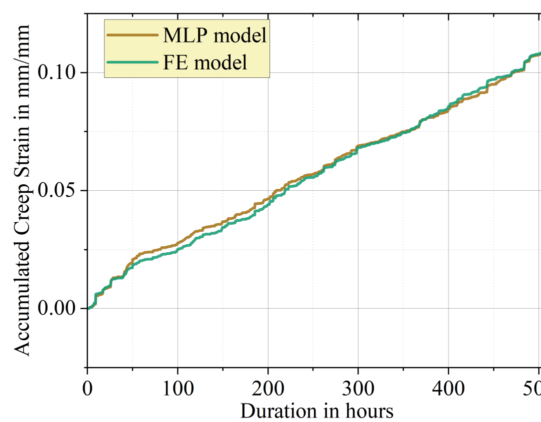

Fig. 3: Evolution of damage indication: Comparison between the accumulated creep strain values from the MLP model and the FE model [4].

3 Solder lifetime modeling

3.1 Method

With the information about the damage increment, different geometric solder joint designs can be compared with each other in terms of damage development. However, in order to be able to make a statement about the consumed and the remaining useful lifetime, a lifetime model is required. The fatigue of solder joints is generally a low-cycle fatigue. Accordingly, the Coffin-Manson relationship was used to model the lifetime [8, 9]. In order to determine the parameters of this relationship for the solder alloy, lifetime experiments were necessary.

For this purpose, specially designed test specimens were constructed on the basis of a bipolar chip resistors of size 1206 (see Fig. 4). By varying the core materials within the circuit board, the fatigue increment introduced into the solder joint per thermal cycle was varied, and the fatigue aging was accelerated. It is important to ensure that the increment is set so that the damage mode corresponds to that of the respective application. In this specific case, creep strain increments were chosen in the range of 6×10^{-3} to $2 \times 10^{-2}\,\mathrm{mm\,mm^{-1}}$. The core thickness was determined using a thermomechanical simulation of the test strip produced with the Ansys APDL software. In addition, each test strip was equipped with a Pt-100 temperature sensor to determine the temperature explicitly present at the test specimen. To ensure quick and smooth replacement of the strips, they were connected and stored via plug-in connectors.

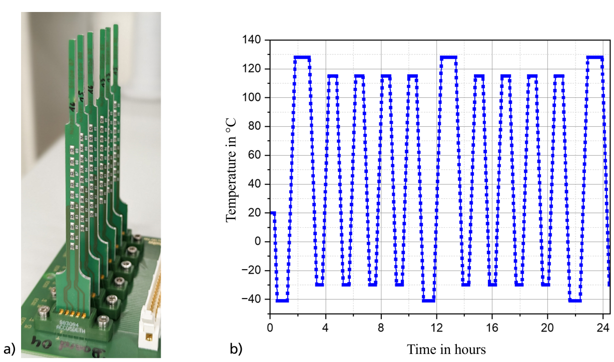

Fig. 4: (a) Solder lifetime modeling samples, and (b) Thermal cycles used in the accelerated testing with the climate chamber.

Since the test specimens were manufactured in conventional electronics production lines, they were also subject to normal technological variations. To keep the influence of these variations to a minimum, each test specimen was checked for geometric deviations (lifting, lowering, tilting, twisting, and offset) of the component using automatic optical inspection, and for solder coverage, void formation and standoff height using X-ray radiography with a resolution of 3 µm per pixel. Using a Design of Experiment (DoE) carried out with the simulation model of the component, the effects on the fatigue increment associated with the measured variables were calculated and evaluated. The test strips selected in this way were then cycled in a Vötsch ClimeEvent C480-70-25 climatic chamber at a temperature profile of $-40\,°\mathrm{C}$ to $125\,°\mathrm{C}$. The temperature rate of change was $5\,\mathrm{K\,min^{-1}}$, and the holding times were set at 30 minutes to ensure that the strip was heated thoroughly and evenly.

The test strips were removed from the climate chamber at regular intervals and subjected to High Resolution Computer Laminography (HRCL), in which the solder joints were checked for cracks and, if present, the crack lengths were determined. In contrast to the usual shear-off test method, this procedure has the significant advantage that the specific individuals can be observed in terms of their fatigue evolution, as the non-destructive analysis method allows the test strips to be returned to accelerated aging after the inspection. The crack progression is classified using a predefined classification of crack lengths into categories I to IV (see Fig. 5 and 6). To determine the failure cycle count, the classic 63.5 % criterion was used for class IV (complete crack). Based on the test with three different damage increments, Fig. 7 was created in which the damage increments are compared with the failure cycle count. The error bars result from the variance in the failure cycle counts of the test specimens and the variance in the fatigue increments according to the DoE analysis.

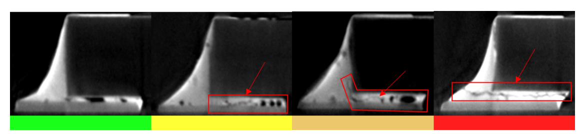

Fig. 5: Crack initiation in the standoff region and eventual propagation through complete solder area.

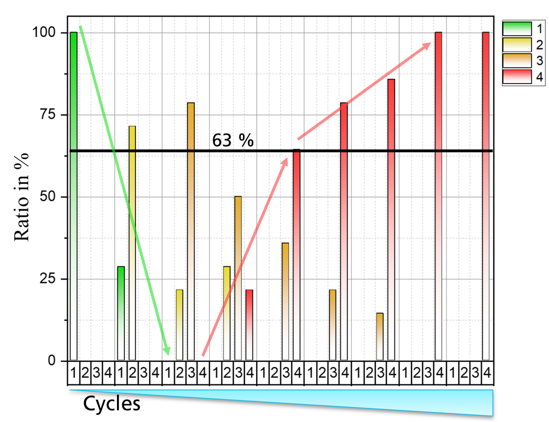

Fig. 6: Damage classification definition used in lifetime modeling. Crack lengths are increasing with thermal cycles and ultimately reach damage class IV.

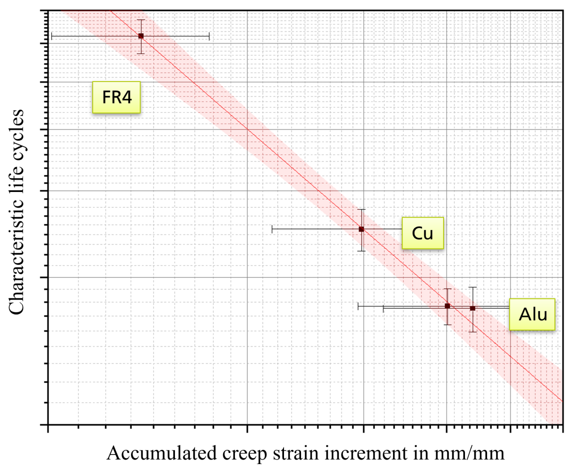

Fig. 7: Sample (solder joint) lifetime model representation derived from the method explained in the text (own measurements).

3.2 Remaining useful lifetime

As explained in the previous section, the number of characteristic life cycles or cycles to failure, N_f, depends on the accumulated creep increment. For demonstration purposes, we consider a lifetime model developed for Sn-Ag-Cu (SAC) alloy developed by Schubert et al. [10], which is given by:

$$N_f = 4.5 \times (\varepsilon_{acc})^{-1.295}. \tag{1}$$

In our case, we have a creep increment per half-cycle, i.e., numbers of half-cycles to failure. Additionally, every half-cycle has a different nature and, hence, different creep increments. To address that, we estimate the consumed lifetime after each half-cycle as [5]:

$$CUL = \frac{1}{N_f}. \tag{2}$$

Then the actual RUL will be,

$$RUL = RUL_{i-1} - CUL_i, \quad i \in \{1, \ldots, m\}. \tag{3}$$

Here, i represents the half-cycle number with m being the maximum and $RUL_0 = 1$. In other words, RUL_0 is the pristine stage with no lifetime consumption and with every half-cycle occurring, RUL will start to decrease. Figure 8 shows the calculated RUL over a test data set which consists of both synthetic and mission profile loads. The RUL calculated from the creep strain increments from the MLP model and FE model are in good agreement, confirming the model accuracy and the suitability of the entire approach.

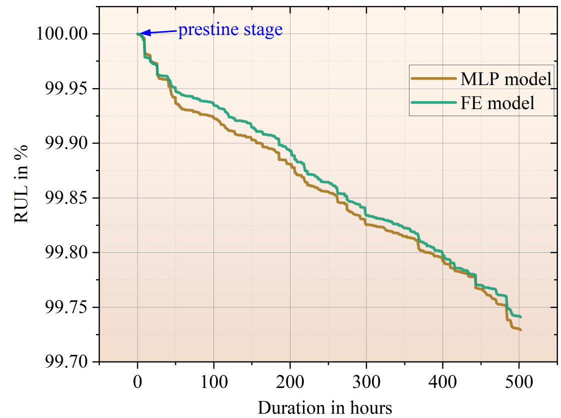

Fig. 8: A comparison of RUL of solder joints predicted with MLP and FE simulation over a test data set.

4 Summary

In this article, authors have proposed a PHM methodology framework applicable to electronic systems. Two major points were addressed: solder joint fatigue prediction and remaining useful lifetime estimation.

In order to develop the fatigue predict methodology, real mission profile loads were measured from a power converter assembly in a tram. Additionally, a synthetic temperature profile was generated. With the help of a digital twin model of the solder joints, fatigue evolution was extracted under both synthetic and mission profile loads. A machine learning model, called MLP, was trained to correlate the temperature features and the corresponding fatigue (creep strain) increments. The model successfully predicted the fatigue increment with R^2-score of 0.93. With this methodology, fatigue prediction even with limited field loading data was achieved. Employment of the ML model further realizes the goal of inline, edge-enabled PHM for electronics.

The solder lifetime modeling was detailed as a second objective. Solder samples creation and accelerated testing conditions were explained. With the help of NDT techniques, failure criteria and damage classification in solder joints were addressed. Ultimately, the RUL calculation was demonstrated over a test data set.

In conclusion, this work presents a PHM methodology for electronics. It helps in developing reliable electronics and anticipate failures in advance. This work can provide the basic structure needed. Further extension to high-value components like QFP, QFN packages as well as different applications like agriculture and aerospace equipment will be studied in the future.

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