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An efficient online time-temperature-dependent creep-fatigue rainflow counting algorithm

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ABSTRACT

Reliability assessment of the materials in real applications in which the materials are exposed to the numerous and complicated time-domain cycles has become one of the most important issues facing all reliability engineers. From offline to online useful lifetime estimations of the material, cycle counting such as Rainflow is paramount of importance. Rainflow algorithm plays the role of transferring complicated time domain cycles to the sorted set of data. This set of data applies to the lifetime model of the material and make the researchers evaluate useful life time of the materials. In this paper, a new online time-temperature-dependent creep-fatigue Rainflow counting algorithm has been proposed. In this new algorithm, online counting of half cycles, time-temperature-dependent mean temperature and creep failure mechanism have been all considered leading to the much more accurate cycle counting and reliability assessment, consequently. This study presents that consideration of the time-temperature-dependent mean temperature and creep failure mechanism can thoroughly impress the reliability assessment in the materials exposed to the temperature cycling. This feature has been validated by employing a set of experimental data of a solder joint, namely the constants of Coffin-Manson-Arrhenius and Monkman-Grant, in a power semiconductor. While the solder joint has been exposed to the specified cycles, the results show that the useful lifetime of the solder joint in the power semiconductor can be estimated with 10% increase in accuracy. The results reveal the importance of the creep failure mechanism and the time-temperature-dependent mean temperature on the reliability assessment.

1. Introduction

Counting of complicated loading cycles applied to any physical systems is increasingly becoming a vital factor in the life time estimation, particularly in the thermo mechanical fatigue study. Cycle counting algorithms are attracting considerable interest due to their capability of compacting a long time history data to the somewhat sorted data expediting the analysis of the fatigue useful lifetime [1,2].

For many years, numerous cycle counting algorithms including peak counting, crossing counting, level counting, simple rate counting, Hayes method, racetrack method, simple range counting, Moshrefifar and Azamfar method and Rainflow counting method have been applied in the various applications [3,4]. In real applications, loading cycles are not in a simple pattern to be counted. Moreover, they do comprise a long-term data which is highly involved to be either analyzed or compared. Fig. 1 depicts two sets of data (temperature), applying to a system. Regarding this figure, it is roughly impossible to analyze that how these two stresses can affect the lifetime of the system. As a reliability point of view, it is also impossible to compare these two stress patterns. However, thanks to the cycle-counting algorithm, analyzing and comparing long and complicated stresses has become possible.

The primary algorithm was established by T. Endo and M. Matsuishi in 1968 [5] based on a rain drop over a Pagoda roof as shown in Fig. 2. Each of the closed hysteresis loop is considered as a load cycle with the specified strain (stress) range and its corresponding mean value. For instance, after applying a specific stress to the material, it starts tensioning (from point ①) leading to the material deformation. This tension continues to point ② in which a new stress makes the material compress to point ③. Then it starts being tensioned and therefore passes point ② leading to form a stress-strain hysteresis loop (③–②) with the strain (stress) range of $|S_{③} - S_{②}|$ and mean value of $(S_{③} + S_{②})/2$. This deformation continues to point ④ and after that a compression stress makes the material strain decrease to point ⑤. Then a positive stress applies and a positive strain occurs (⑥). After that by compressing the material, a material deformation occurs and by passing through point ⑤ another stress-strain hysteresis loop is formed (with the range of $|S_{⑥} - S_{⑤}|$ and mean value of $(S_{⑥} + S_{⑤})/2$). The process will be continued till all the data has been analyzed.

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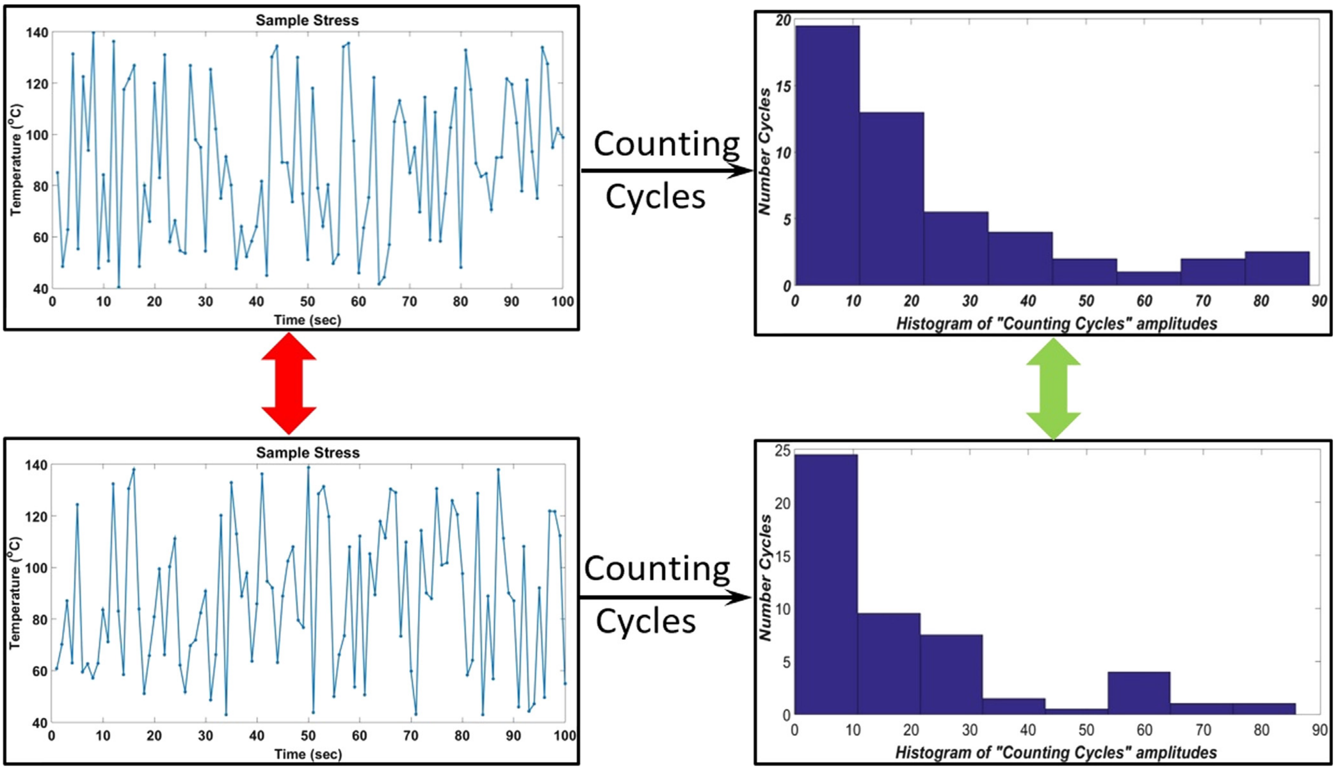

Fig. 1. Time domain data versus cycle-counting domain.

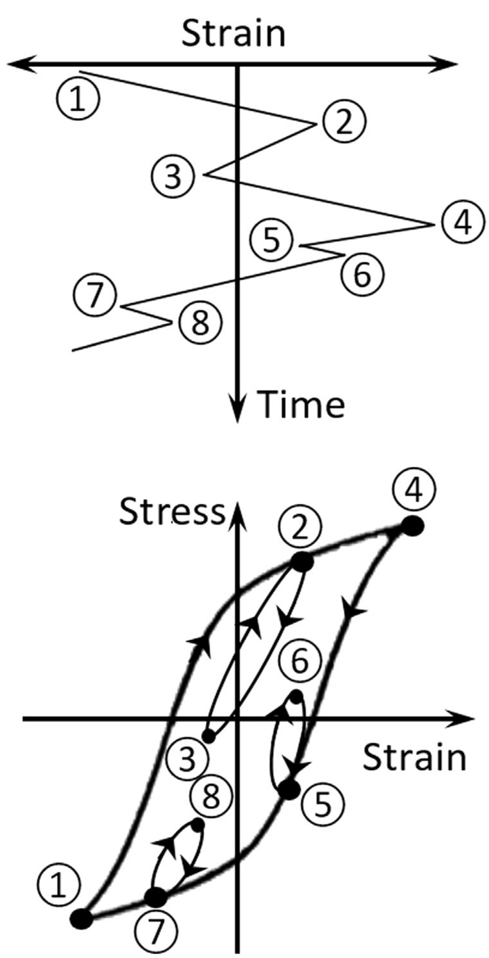

Fig. 2. Time domain data and its corresponding stress-strain hysteresis loop.

As it was mentioned, there are numerous cycle-counting algorithms [3]. Among all of them, Rainflow algorithm has gained lots of attractions owing to its simplicity of implementation and insignificant errors [6–8]. As the procedure of algorithm performing point of view, Rainflow algorithm generally falls into two categories, namely, three-point and four-point [9–11].

Although McInnes and Meehan [12] have mathematically proved that the three-point and the four-point methods are both equal, the three-point algorithm gains much popularity between engineers [13]. Based on the ASTM E1049-85 standard [9], the three-point Rainflow algorithm coding was implemented by Nieslony [14] using MATLAB tools. Rainflow is based on the local maxima and minima of the time domain data history. It means that for applying Rainflow cycle counting algorithm (either in three-point or four-point cases) to the time domain data history, it primarily needs to be transferred to the local extrema. In addition, all the time domain data history has to be known which makes online cycle counting encounter to some sort of difficulties.

As an example based on the codes which was composed by Nieslony [14], a sample thermal cycle as shown in Fig. 3a has been considered. Regarding Fig. 3a, cycle counting of this thermal load history is thoroughly complicated and hence necessity of utilizing Rainflow algorithm is evident. Based on the method, firstly load cycles have to be transferred to their extrema. For obtaining extrema, the method uses discrete second-order derivative of load cycles. The extrema of sample load history is also drawn in Fig. 3a. Based on the full time-temperature data (load history) and extracted extrema, MATLAB codes tried to find full and half cycles. As shown in Fig. 3b there are 16 half cycles up, 17 cycles down and 13 full cycles.

Cycle-counting algorithms, particularly Rainflow, are widely used in mechanical engineering, vibration system and power semiconductor thermo-mechanical applications [15–18]. In many applications, for online estimating lifetime consumption of an interested part in a system, an online Rainflow is undoubtedly required [19]. In the conventional Rainflow either based on the three-point or on the four-point algorithms, the whole time domain history must be specified before