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High cycle fatigue behaviour and generalized fatigue model development of lead-free solder alloy based on local stress approach

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ABSTRACT

This paper gives an insight into high cycle fatigue (HCF) behaviour of a Pb-free solder alloy in the region between 10^4 up to 10^9 fatigue cycles using fatigue specimen. By means of a local stress approach, the method can be translated into solder joint fatigue evaluation in an application. The effect of temperatures (35 °C, 80 °C, 125 °C) on the fatigue property of Pb-free solder alloy is considered in this work to understand the possible fracture mechanisms and micro structural changes in a solder alloy at elevated temperature. Experiments are performed for different interaction factors under mean stresses ($R = 0, -1, -3$), stress concentration (notched, un-notched) and surface roughness. SN (stress-life) diagrams presented in this work will compare the fatigue performance of $Sn_{3.8}Ag_{0.7}Cu$ solder alloy for different conditions. Furthermore, mathematical fatigue model based on FKM guideline (in German "Fachkuratorium Maschinenbau) is extracted out of the experiments under all these external effects. The models can be exported later for lifetime evaluation purposes on applications. The paper thereby proposes the use of FKM guideline in the field of microelectronics.

1. Introduction

Applications like automotive electronics in power-train segments often experience vibration together with temperature in service [1]. Studies on other applications like aircraft systems account for 20% of electronic failure due to vibration, as compared to the 55% from thermo-mechanical fatigue failure [1]. For SnPb alloys, plenty of efforts have been made in past to address the issue of fatigue [2–4]. It is evident that most of the literature on solder reliability refers to performance under relatively low cycle (<10^4 cycles) fatigue conditions, whether imposed thermally, mechanically or both [5–11]. A generalised lifetime prediction tool or methodology is therefore a requirement in industries to predict the fatigue life during the product development phase for solder joints. For SnAgCu (SAC) alloys, HCF experiments were done by researchers and industries [1,12–16] directly on surface mounted technology (SMT). Often, experiments were conducted on application level to understand the failure modes or to create failure models. Even though it is a common practise to conduct experiments on application level, it is an expensive process in terms of cost and time. Normally, the whole cycle of application testing has to be repeated, when components/materials are changed.

Another possibility is investigating HCF in a laboratory on specimens (coupon level). One of the few studies that are related to the HCF specimens on coupon level was a stress-controlled fatigue experiment at 2 Hz but only up to 10^5 cycles on a bulk specimen with interface [17]. It is also reported that there is a transition in crack propagation mechanism, when the strain is up to a critical value for the $Sn_{3.5}Ag$ solder [17]. These mechanisms were not clearly indicated. The effect of cyclic loading is investigated in this paper for SAC alloy. For generic purpose, the bulk solder specimens were investigated under HCF conditions for different temperatures. This enables one to study the possible deformation and fracture mechanisms encountered in solder material under combined fatigue and temperature conditions. It was observed from the vibration experiments on SMT's from Meier et al. [16], Yang et al. [15], that the crack failure initiates mostly from the stress concentration regions of the solder joints. The convex and concave solder joint geometry creates a high-stress gradient region, which could potentially over predict

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the stress for lifetime prediction. This is the reason a notched and unnotched specimen is replicated in this study to investigate the material dependent stress-gradient corrections.

The overall idea of this work is to generalise the lifetime assessment of SMT component solder joints under vibration loads. This approach can be later used in finite element (FE) tools. This generalisation work revolves around the idea of using the solder specimens on coupon level instead of testing on components directly to assess the lifetime. Fatigue model results based on FKM guidelines-2003 version [18] are used in this study, as the software (used in this investigation: nCode Designlife™) is still based on 2003 version. The FKM guideline is used to transfer the experiment data based on coupon level to the analysis of real components. In the FKM guideline influences like mean stress, roughness, stress gradient are considered. The FKM guideline is well accepted in civil engineering for steel and aluminium. In this paper, the FKM guideline is adapted for solder joint performance evaluation.

The results of the HCF experiments on coupon level can be validated for the failure assessment of solder joints in microelectronics application, using FE approaches coupled with fatigue analysis software. This paper however only discusses the fatigue models and the consequent FKM guideline modifications.

2. Experimental procedure

Solder tensile bars of $Sn_{3.8}Ag_{0.7}Cu$ (wt.%) alloy from Stannol Corporation, were used in this study. By means of a "re-melting" process in a special heated aluminium die, specimens can be cast with a good surface quality, without macro-cracks and edges. The details of solder specimen processing is described elsewhere [19].

The specimens were manufactured as seen in Fig. 1(a) and the longitudinal sections were compared to that of SMT component solder joints during the preliminary phases to replicate the microstructures like dendritic orientations and intermetallic particle sizes. The primary grain structure is oriented along the flow direction as seen in Fig. 1(b). All fatigue experiments were performed on an Instron E3000™ machine. Each fatigue specimen is attached to a precise extensometer over the measurement region to monitor the strain. For both notched and unnotched specimens, a 30 mm long extensometer is used for the strain calculation. The whole setup features a controlled climate chamber to account temperature variations.

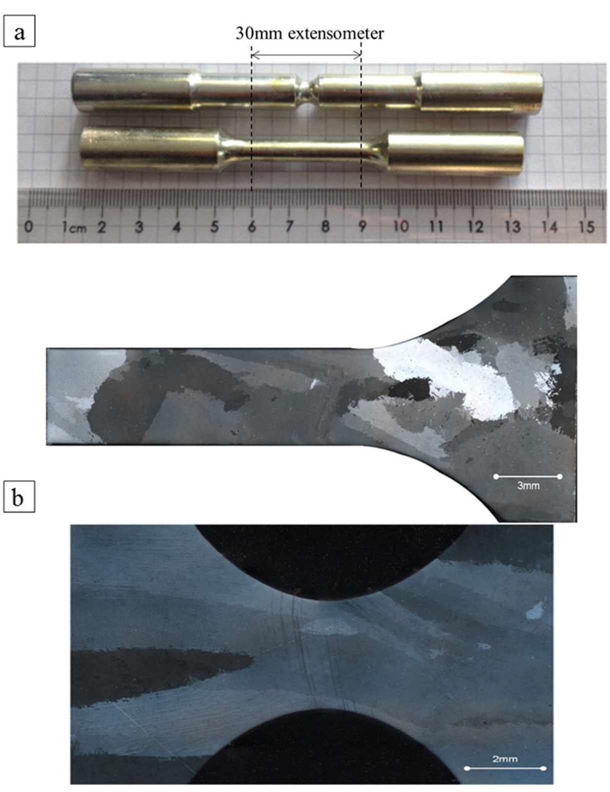

Fig. 1. (a) Manufactured fatigue solder specimens (notched and unnotched) taken out from the aluminium die, (b) cross-polarized optical cross section images of the cast solder specimen showing the primary grains along flow direction, on unnotched & notched specimen.

3. Experimental results

The result section is incorporated with three major steps. Firstly, fatigue parameters were determined from uniaxial experimental results for various load cases. The load cases are the possible influential parameters on fatigue of solder alloys such as mean stress, stress gradient, temperature, and roughness. The experiments were carried out in the range between 10^4 up to 10^8 cycles, with a common frequency of 60 Hz, which was maintained throughout the experiment.

Next, the strain progressions were measured during the fatigue experiments, which are studied with variants of mean stress, temperature and stress amplitude to observe any possible cyclic softening or hardening effects. These results will be discussed together with the micrographs and strain amplitude observations. The stresses in the paper will be referred low stress (LS), medium stress (MS) or high stress (HS). The classification of stress (LS, MS, or HS) is based on the fatigue mechanism as brittle failure or plastic dominated failure.

Finally, fatigue models with the influence of the external factors will be modified using Basquins equations for the local-stress based lifetime prediction. Specific guidelines from FKM version 2003 [18] were used to perform such kind of modifications, as the SAC alloy material constants have to be determined for roughness, stress gradient, and mean stress effects.

The overall fatigue results can be discussed based on influential parameters as follows:

- Fatigue property under temperature variant,
- Fatigue property under mean stress influence,
- Stress gradient effects,
- Surface roughness influence on fatigue life.

3.1. Fatigue property under temperature variant

This section discusses results of the fatigue property for various temperatures. Fig. 2. Normalised SN diagram at different temperatures at 60 Hz, $R = -1$ (symbols represent measured points and dotted line shows the fit based on Basquins Eq. (1)) shows the relationship

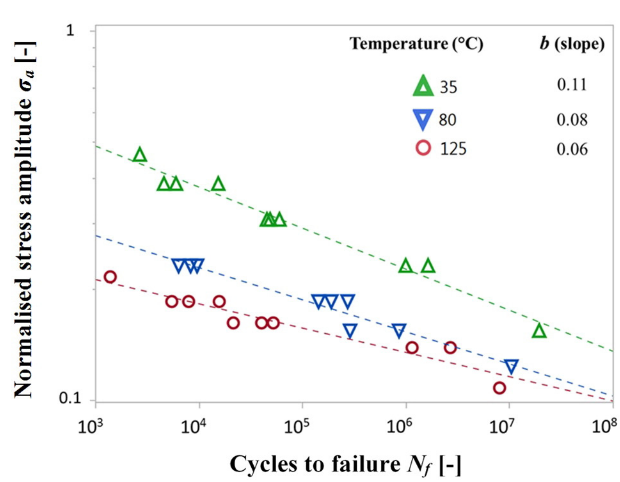

Fig. 2. Normalised SN diagram at different temperatures at 60 Hz, $R = -1$ (symbols represent measured points and dotted line shows the fit based on Basquins Eq. (1)).