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The role of stress state and stress triaxiality in lifetime prediction of solder joints in different packages utilized in automotive electronics

M. Kuczynska [a,c,*], N. Schafet [a,**], U. Becker [a], B. Métais [b,c], A. Kabakchiev [b], P. Buhl [c], S. Weihe [c]

[a] Robert Bosch GmbH, Automotive Electronics Division, Postfach 300240, 70442 Stuttgart, Germany
[b] Robert Bosch GmbH, Corporate Research Division, Postfach 300240, 70442 Stuttgart, Germany
[c] Materials Testing Institute (MPA) University of Stuttgart, Pfaffenwaldring 32, 70569 Stuttgart, Germany

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ABSTRACT

This work presents an overview on the role of the stress state and stress Triaxiality Factor (*TF*, see Eq. (1)) in lifetime prediction of solder connections. According to various literature sources, the *TF* is one of the most important factors influencing initiation of ductile fracture (Bao and Wierzbicki, 2004; Davis and Connelly, 1959). It is widely reported that lifetime of the ductile materials decreases under hydrostatic tension when combined with high *TF*-values. Recent investigations report that the compressive hydrostatic stress state combined with a high shearing load and low (or even zero) *TF*-values also contributes to failure (Bao and Wierzbicki, 2005; Kweon, 2002; Nielsen and Tvergaard, 2011).

Two package types, the Loss Free Packaging (LFPAK) and the Plastic Ball Grid Array (PBGA), were investigated by means of FE-simulation on Board- and System-Level, and presented damage prediction was compared with an experimental data. In the LFPAK and BGA solder joints the regimes of hydrostatic tension and compression during temperature cycles are evaluated and compared with distribution of equivalent von Mises stress, stress intensity (maximum shear stress) and triaxiality factor. The multiaxial effects were included in both, lifetime prediction and fracture location: the damage related variables, inelastic strain and energy density, were modified in an APDL post-processing routine based on the state of hydrostatic stress and corresponding *TF* for each time increment. Further, using a simplified simulation approach, the path of the crack propagation was calculated according to the distribution of the *TF*-modified and non-modified inelastic strain. It is shown that when including multiaxial effects by modification of damage related variables a better correlation between calculated and experimentally observed crack path is achieved.

1. Motivation

The electronic industry puts high effort into achieving accuracy in lifetime prediction by better understanding of the following aspects: solder material behavior, influence of the package's warpage and the environment conditions, for example when mounted in Engine Control Units (ECUs). A combination of bending and shearing load conditions, originating from the thermally induced warpage and thermal mismatch between the materials, causes unique, multiaxial stress state imposed onto solder interconnections.

Damage in ductile materials has been linked with volume growth of microscopic voids and their coalescence, which are enhanced under hydrostatic tension (study of void growth by McClintock [1], Rice and Tracey [2], Gurson [7]), and take place before damage can be observed on macroscopic scale. The strong dependency of these phenomena on the tensile hydrostatic stress and effects on material ductility (the higher the tensile hydrostatic stress, the more brittle can be the response of the material [3,15]) has been investigated by means of dimensionless triaxiality factor *TF* [16]. For increasing positive hydrostatic stress the damage in the material was observed to increase exponentially [1].

While the physics of damage has been widely investigated and explained for positive *TF* [1,2,4,7], recent studies show that the damage can also occur for the compressive hydrostatic stress [5,6,8].

Kweon [8,14] looked for physical mechanisms able to explain damage at zero and negative triaxiality by means of the crystal-plasticity-based models, i.e. on the grain-to-grain interaction level. The results of his study show that the damage driving force is the development of the hydrostatic stress gradients, which lead under shear deformation to a tensile hydrostatic stress in the grain-to-grain interaction. Nielsen and Tvergaard [9] point out that such damage can be observed in form of smeared-out dimples on the fracture surface, and the mechanism

* Correspondence to: M. Kuczynska, Robert Bosch GmbH, Robert-Bosch-Strasse 2, 71701 Schwieberdingen, Germany.
** Corresponding author.
E-mail addresses: marta.kuczynska@de.bosch.com (M. Kuczynska), natalja.schafet@de.bosch.com (N. Schafet).

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governing this type of failure is interaction of the primary voids, their rotation and elongation until severe plastic deformation of the internal ligaments.

Bao and Wierzbicki [6] proposed $TF = -1/3$ (in their definition $TF = \sigma_m/\sigma_{EQV}$, where $\sigma_m = 1/3\,\mathrm{tr}(\sigma)$) as a cut-off value, under which fracture was proven not to occur.

Wierzbicki in his investigation [5,6] on aluminum alloy underline the role of stress triaxiality in initiation of the ductile facture. He proposed a quantification of influence of the different triaxiality states onto equivalent strain to fracture shown in the Fig. 1. Three regions have been recognized:

(A) In tension region starting from TF = 0.4 (nearly uniaxial stress state in tension), where strain to fracture decreases with increase of stress triaxiality,
(B) Combined shear and tension region under low positive triaxiality, where the strain to fracture for aluminum was suspected to decrease when approaching $TF = 0$, i.e. pure shearing (the real trend however unknown),
(C) Combined shear and compression region, where $TF < -1/3$ is identified as non-damaging region. Kweon [8] explained this boundary by lack of any shear component at $TF = -1/3$, and beyond this value the shear damage effects are minimized by high compressive stress.

In order to incorporate these effects into lifetime prediction Manson and Halford [13] proposed in 1977 the multiaxiality factor (*MF*) corrector for increments of inelastic strains based on the current state of *TF* (Eq. (1)) defined as ratio of the first stress invariant $I_1 = \mathrm{tr}(\sigma)$ to equivalent von Mises stress:

$$TF = \frac{tr(\sigma)}{\sigma_{Mises}} \tag{1}$$

$$MF = TF \; for\, TF \geq 1, \quad \text{else } MF = \frac{1}{2 - TF} \tag{2}$$

$$\Delta^* \varepsilon_{eq}^{in} = MF \cdot \Delta \varepsilon_{eq}^{in} \tag{3}$$

Two regions of its influence were determined, where for $TF > 1$ ($TF = 1$ uniaxial case) the inelastic strain increment Eq. (3) was amplified by factor $MF = TF$, whereas for the $TF < 1$ (transition from tension through pure shearing to compressive load), the strains were decreased based on the $MF = {}^{1}/_{(2\,-\,TF)}$ relation. It was reported, that a good correlation was achieved for $TF < 1$, however for a high triaxiality stress state the results were not satisfying.

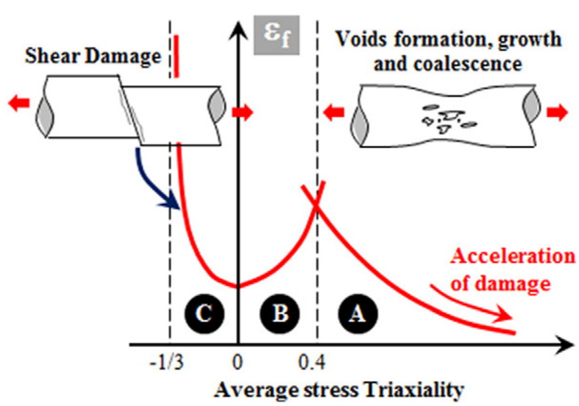

Fig. 1. Schematic three branch fracture model: dependence of the equivalent strain to fracture on the average stress triaxiality of Al2024-T351 defined by Bao and Wierzbicki [5]; (A) Tensile enhanced exponential amplification of the damage; (B) Two competing damage mechanisms: shear decohesion and void formation; (C) Dominance of shear decohesion.

The importance of investigations of solder behavior under multiaxial stress state is also recognized in the solder community. Several works have been published for study of multiaxial effects in tin-based alloys [17,24,25,26,27], where the study was performed for bulk samples under push-pull torsional load. Lederer [23] has successfully incorporated dependency of pressure in the constitutive model describing the pressure dependence of plasticity and fracture in solder joints.

Our first investigation of the influence of the multiaxial effects on the accuracy of lifetime prediction described in [11] showed that post-processing based implementation of this approach produced better correlation with experimental lifetime results.

In this work, the principle of strain increment modification is incorporated to understand the influence of multiaxial loads in a wide range of *TF*-regimes in application of electronic packages LFPAK and BGA.

2. Investigated cases

This paper focuses on the FE-Simulation based investigation of the multiaxial stress state in the solder joints of LFPAK and BGA packages under different set-up affecting their stress state.

2.1. LFPAK package

2.1.1. Set-up

The LFPAK Package is investigated on the System (ECU) and Board Level (in the Board Level Reliability tests). In the ECU (Fig. 2) its location was defined near a screw connecting the systems housing.

The package simulation under TC-load was performed using the sub-modelling technique, with displacement and temperature fields imposed from transient thermo-mechanical simulation of the entire ECU (similar to [10]). The non-linear material properties used in the simulation: a) visco-elastic for the epoxy mold compound and PCB, b) secondary creep model for the SnPb-solder used as the die attach and c) visco-plastic material model for SnAgCu solder joints (Chaboche model, characterized like in [12], available in Ansys 17.0). The sub-model

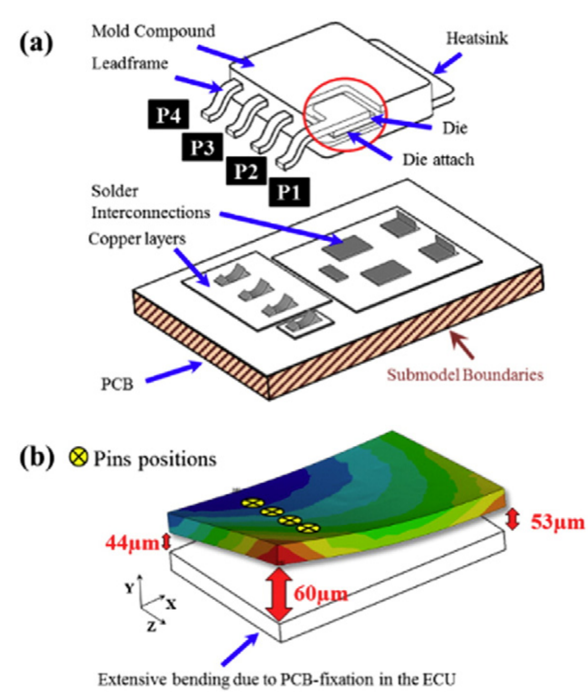

Fig. 2. (a) LFPAK package composition, and position of the pins (b) Difference in out-of-plane displacement of PCB between T_{min} and T_{max} showing clear influence of neighboring screw connection.