Comparative Study of Plastic Strain Accumulations at Thermal Cycles for Solder Alloys

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Abstract. This paper presents an investigation of plastic strain accumulation at thermal cycles for 4 different solder alloys used in electronics. The investigation was performed on an assembly which is part of an electronic packaging. The behavior of the solder was numerically analyzed by means of the finite element method, using Ansys program. This work was carried out for a thermal variation of 165°C, in the range of -40...+125°C. The first material (60Sn40Pb) was described using Elastic-Plastic, Chaboche and Anand models, which combine the plasticity with creep. Following the investigation of the first solder alloy, a correlation between the Anand model and the Elastic-Plastic one was proposed, this being obtained by using a numerical constant. It was observed that the proposed correlation factor is closely related to hardening constant (a parameter of the Anand model). Following the first investigation, another 3 types of solder alloys were also analyzed. Each new material was described with both the Anand model and the Elastic-Plastic model. The possibility of correlation between the two models, as well as the verification of the relationship between the used correlation factor and hardening constant, were investigated. Following these investigations, it was concluded that, for the studied thermal field, the material models can be correlated. Also, for 50% of investigated cases, the correlation factor is closely related with a parameter of the Anand model.

1. Introduction

In electronics are used many different soldering materials. The major problem occurs when the material is subjected to repeated thermal cycles, and these lead to plastic strain accumulations, initiation of cracks in tin and then fracture. Thus, damage to soldering material occurs.

In the past three decades a lot of analytical, numerical and experimental investigations, regarding the viscoplastic behavior of different kind of materials have been performed. In 1985, Anand [1], develops constitutive equations which describe the elastic-viscoplastic behavior of metal materials, considering small elastic stretches and large plastic deformations. This developed material model does not require a yield conditions and attendant loading criteria. Moreover, the model has defined only one scalar parameter which is isotropic resistance to plastic flow. In a word, the model proposed by Anand combine the plasticity with creep, and its constitutive equation is a combination of 9 material parameters. Afterwards, Brown and coworkers [2], develop constitutive equations which model large elastic-viscoplastic deformations of metals at high temperatures. Cheng and coworkers [3] apply the Anand model to study the plastic deformations for solder alloys, also performing experimental tests to determine the parameters of model. For studied cases (4 types of solder), constitutive equations accurately reproduce the basic tests. Busso and coworkers [4] analyze a solder alloy by applying thermal cycles to predict the shape of plastic strain and material microstructure evolution. Wang and coworkers...
[5] use the Anand model to study the plastic deformation behavior of 4 soldering materials used in a series of electronic packaging. Liu and coworkers [6] investigate the inelastic behavior for 2 solder alloys, at both high temperature and different strain rates. Chen and coworkers [7] use a modified Anand model to describe plastic deformation for solder materials used in electronics, at temperatures between -40 and 125°C. Also, in this article is performed a comparison between analytical and experimental results.

Considering all these problems which can occur during the operation of a product (plastic strain accumulation, initiation and propagation of cracks in material and brake of it, respectively), it is necessary to perform in-depth investigations in terms of material viscoplasticity and in their comportment at thermal cycles. The main objective of this paper is the comparative investigation of the behavior of an electronic assembly, subjected to temperature cycles. Various material models, such as elastic-plastic with kinematic and isotropic hardening, the Chaboche model and the Anand model were used.

2. Material models

In order to describe the solder alloys, three material models (Elastic-Plastic model, Chaboche model and Anand model, respectively) were used.

In the case of Elastic-Plastic model, material properties for each solder alloy are shown in Table 1. For first round of analyses, 6 models of elastic-plastic model were described, with two types of hardening. Therefore, for both hardenings (isotropic and kinematic) 3 different tangent modules, $E_t$, namely: (i) $E_t = 0$ [MPa], (ii) $E_t = E/10^4 = 3$ [MPa] and (iii) $E_t = E / 100 = 300$ [MPa], were used.

| Solder Alloy | $\rho$ [kg/m$^3$] | $\alpha$ [C$^{-1}$] | $R_{p02}$ [MPa] | $\nu$ [-] | $E$ [MPa] | $E_t$ [MPa] | Hardening       |
|--------------|-----------------|-----------------|----------------|--------|---------|----------|----------------|
| 60Sn40Pb     | 8 600           | 2.4$\cdot$10$^{-5}$ | 32             | 0.4    | 3.1$\cdot$10$^4$ | 0        | 3 300         | Iso. & Kin.    |
| 62Sn36Pb2Ag  | 8 600           | 2.45$\cdot$10$^{-5}$ | 38             | 0.35   | 3.44$\cdot$10$^4$ | 0        | Isotropic     |
| 96.5Sn3.5Ag  | 7 360           | 2.185$\cdot$10$^{-5}$ | 34             | 0.4    | 5.27$\cdot$10$^4$ | 0        | Isotropic     |
| 92.5Pb5Sn2.5Ag | 11 110         | 2.95$\cdot$10$^{-5}$ | 17             | 0.33   | 1.38$\cdot$10$^4$ | 0        | Isotropic     |

In Table 1, the parameters are: $\rho$ – density; $\alpha$ – coefficient of thermal expansion; $R_{p02}$ – yield stress; $E$ – Young modulus; $E_t$ – tangent modulus.

Material model proposed by Chaboche [8] defines a combined behavior for both kinematic and isotropic hardening. It is used for evaluating the effects of cycle loadings and for model both of cycling hardening and softening. To define the behavior of material described by Chaboche model, 3 material constants are necessary: (i) yield point, $R_{p02} = 32$ [MPa], (ii) linear kinematic hardening, $C = 13.6$ [MPa] and (iii) dynamic recovery coefficient, $\gamma = 457.9$ [-]. This last term introduces the nonlinearity between the back stress and the actual plastic strain. The values for $C$ and $\gamma$, in case of 60Sn40Pb, were taken from paper of Basaran and coworkers [9].

As specified above, the material model performed by Anand is based on a 9-parameter equation. For the study investigated in this paper, the values for all parameter were taken from Ref. [5].

In Table 2, the following parameters were used: $s_0$ – resistance to initial deformation; $A$ – pre-exponential factor; $\xi$ – multiplier of stress; $m$ – strain rate sensitivity; $h_0$ – hardening/softening constant; $\xi$ – saturation value of deformation resistance; $n$ – strain rate sensitivity for the saturation value of deformation resistance; $a$ – strain rate sensitivity of hardening/softening; $Q/R$ – activation energy/gas constant.
Table 2. Anand parameters for all used materials.

| Parameter | 60Sn40Pb | 62Sn36Pb2Ag | 96.5Sn3.5Ag | 92.5Pb5Sn2.5Ag |
|-----------|----------|-------------|-------------|----------------|
| $s_0$ [MPa] | 56.330 | 42.320 | 39.090 | 33.070 |
| A [Hz] | $1.49 \cdot 10^7$ | $2.3 \cdot 10^7$ | $3.3 \cdot 10^6$ | $1.05 \cdot 10^5$ |
| $\zeta$ [-] | 11 | 11 | 6 | 7 |
| $m$ [-] | 0.303 | 0.303 | 0.182 | 0.241 |
| $h_0$ [MPa] | 2 640.8 | 4 121.31 | 3 321.15 | 1 432 |
| $\dot{s}$ [MPa] | 80.420 | 80.790 | 73.810 | 41.630 |
| n [-] | 0.0231 | 0.0212 | 0.018 | 0.002 |
| a [-] | 1.34 | 1.38 | 1.82 | 1.3 |
| $\theta_R$ [K] | 10 830 | 11 262 | 8 900 | 11 010 |

3. Finite element analysis

The study presented in this paper was performed on an assembly (part of an electronic packaging) presented in Figure 1. The assembly is composed by a plastic skeleton (1) which is over molding to a pin (2). The connection between pin and PCB (3) are made by a solder alloy (4).

![Figure 1. CAD model for analysis](image)

Boundary conditions were chosen considering the missing parts of assembly. Therefore, both for lateral faces and for rear sides it was used a frictionless support, which allow the sliding in its plane. To block the rigid body motion, the displacement on Z axis of a horizontal edge was suppressed (Figure 2a). The contacts between all parts (1-2, 2-4, 3-4) were defined as bonded (Figure 2b).
Due to the fact that the main subject of this investigation is the solder alloy, which has small dimensions, it was used a fine meshing for it (elements with an approximate dimension of 0.1 mm). Considering time reduction of analysis, all other parts was meshed with a larger dimension than solder alloy’s elements. All meshed assembly is presented in Figure 3.

The whole assembly was subjected to a thermal condition with the charging scheme shown in Figure 4. The temperature varies between -40 and 125 °C, having a charging time of 300 s (5 minutes), and a maintenance of 1500 s (25 minutes).
4. Results

It must be mentioned that the running time for an analysis in Ansys [10], using a material described with Anand model, is approximately 8 times higher than for the other models. Due to this reason, the investigation for possibility of correlation between models were performed. First of all, the behavior of 60Sn40Pb was investigated by running 6 analyses using Elastic-Plastic model, one analysis with Chaboche and one with Anand material model. The results are shown Figure 5. The curves for two Elastic-Plastic models were not represented because of their similarity with the others.

After running the analyses with Anand (the reference model), it was obtained a plastic strain accumulation of 0.2 [mm/mm], for an interval of 9 000 s. Also, it was proposed a correlation between Chaboche and Anand, and Elastic-Plastic (Et=0 MPa) and Anand, respectively, for the studied time period.
After the investigation and the interpretation of results, it was observed that if the values of models are multiplied with a constant equal with 2.7, both of Elastic-Plastic (Figure 6a) and Chaboche (Figure 6b) are closely similar with reference model, Anand, on the investigated domain. On the other hand, this thing is not happening for the other material models; in case of these can be observed significant differences (up to 40%) between them and Anand (Figure 6c, 6d).

Figure 6. Correlation between Anand and the other models

There can be observed a close relationship between the correlation factor (2.7) and the value of hardening constant, $h_0$. It can be easy to see that the correlation factor is approximately equal with hardening constant divided with 1 000. Due to this reason, the investigations continue for another 3 solder alloys. But, for these, were used just two material models: Anand (because it is the reference one) and Elastic-Plastic with $E_t=0$ MPa, in expense of Chaboche, due to its simplicity of parameters determination.

The results for the other 3 materials (62Sn36Pb2Ag, 96.5Sn3.5Ag and 92.5Pb5Sn2.5Ag) are shown in Figure 7. For 62Sn36Pb2Ag was used 2.9 as correlation factor, the hardening constant being 4 121.31 MPa; for 96.5Sn3.5Ag was used 3.3, while $h_0 =3 321.15$ MPa; for 92.5Pb5Sn2.5Ag was used 2.3 and its hardening constant has a value of 1 432 MPa.
It can be easy to see that just in one case of the last three, the correlation factor is closely related to Anand parameter, hardening constant. But it can be said that for all investigated cases, in 50% of them, the correlation between these two constants is possible, with proposed formula.

5. Conclusions
In this paper are presented results of investigations effectuated to characterize the behavior at thermal cycles of 4 solder alloys, namely 60Sn40Pb, 62Sn36Pb2Ag, 96.5Sn3.5Ag and 92.5Pb5Sn2.5Ag. During the study, the plastic strain accumulation at thermal cycles was investigated, by using 3 material models. The study was performed for a thermal variation of 165°C, in range of -40...+125°C (shown in Figure 5).

Time for running an analysis with finite elements, for each kind of material model, is different. In case of Anand model, time for running is 8 times higher than in case of the other 2 material models. Due to this problem, the possibility of correlation between models was studied.

It was proposed a constant to correlate the material models. Between correlation factor and value of hardening constant was observed a close relationship, according to formula $\frac{h_0}{1000}$.

In Table 3 are shown the results for all investigates materials.
Table 3. Hardening constant vs. correlation factor

| Solder Alloy       | Hardening constant $h_0$ [MPa] | Correlation factor |
|-------------------|--------------------------------|--------------------|
| 60Sn40Pb          | 2 640.8                        | 2.7                |
| 62Sn36Pb2Ag       | 4 121.31                       | 2.9                |
| 96.5Sn3.5Ag       | 3 321.15                       | 3.3                |
| 92.5Pb5Sn2.5Ag    | 1 432                          | 2.3                |

After all investigations, can be concluded that for studied thermal domain, the material models can be correlate. Also, for 50% of investigated cases, the correlation factor has a close relationship with a parameter of Anand model, hardening constant.

6. References
[1] Anand L 1985 *Int J Plasticity* 1 213-231
[2] Brown SB, Kim KH and Anand L 1989 *Int J Plasticity* 5 95-130
[3] Cheng ZN, Wang GZ, Chen L, Wilde J and Becker K 2000 *Solder Surf Mt Tech* 12(2) 31-36
[4] Busso EP, Kitano M and Kumazawa T 1994 *J Electron Packaging* 116 7-15
[5] Wang GZ, Cheng ZN, Becker K and Wilde J 2001 *J Electron Packaging* 123 247-253
[6] Liu JC, Yu HJ, Zhang G, Wang ZH and Ma JS 2014 Constitutive behavior and Anand model of novel lead-free solder Sn-Zn-Bi-In-P. *Proc of the Int Conf on Electronics Packaging (ICEP)*, Toyama International Convention Center, Japan, 23-25 Apr 2014, 156-161
[7] Chen X, Chen G and Sakane M 2005 *IEEE T Compon Pack T* 28 111-116
[8] Chaboche JL 1986 *Int J Plasticity* 2 249
[9] Basaran C, Zhao Y, Tang H and Gomez J 2004 *J Electron Packaging* 127(3) 208-214
[10] ANSYS® Academic Research, Release 17.1

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