A Compilation of Anand Parameters for Selected SnPb and Pb-free Solder Alloys

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***Abstract*—Finite-element (FE) simulation is widely used in electronic packaging. It is particularly useful in the design of solder joint attachments. To ensure fidelity, FE simulation must capture the highly nonlinear behavior of solder. One useful material model for solder is Anand's viscoplastic model. A compilation of Anand parameters reported in the literature for a variety of solder alloys is provided.**

***Index Terms*—Electronic packaging, viscoplasticity, reliability, simulation, SMT, solder joint, finite element analysis, Anand, solder fatigue.**

Introduction

Surface-mount technology (SMT) has grown through the decades to dominate the design of electronic products and systems. SMT joints are an important aspect of system design, in that they provide electrical, mechanical, and thermal coupling to the next-level component. Ensuring the robustness of SMT joints is, therefore, a key consideration.

One well-established test to measure joint robustness is accelerated temperature cycling (ATC). ATC test conditions can vary, but standard levels have been defined for several product categories [1]. Vast quantities of test data have been generated over the years, but ATC testing incurs significant cost and requires a significant amount of time to complete.

One means of reducing the amount of ATC testing is through finite-element analysis (FEA). FEA is widely used in electronic packaging to guide the design of products and experiments. A properly validated FE model can also provide insight into failure mechanisms and help in the development of industry standards. One obstacle to accurate FEA is capturing the complex nonlinear behavior of solder at the high homologous temperatures (T_H) often seen during product manufacture and in end-use environments.

Solder Behavior and Anand Parameters

Numerous material models have been reported in the literature including simple elastic, elastic-plastic, creep, and viscoplastic. Notably, Anand's viscoplastic model [2], [3] has enjoyed popularity in the packaging literature. The reader is referred to the original publications for details regarding the Anand model. Nine parameters are needed to fully define an Anand material and are listed in Table I.

In brief, Anand's model consists of a flow equation governing the inelastic strain rate $\dot{\epsilon}_p$:

$$\dot{\epsilon}_p = A\ exp\left(\frac{-Q}{RT}\right)\left[sinh\left(\xi\frac{\sigma}{s}\right)\right]^{1/m} \tag{1}$$

and two evolution equations governing the internal state variable s and its saturation value s^*:

$$\dot{s} = \left\{h_0\left|1-\frac{s}{s^*}\right|^a \cdot sign\left(1-\frac{s}{s^*}\right)\right\}\cdot\dot{\epsilon}_p\ ;\quad a>1 \tag{2}$$

$$s^* = \hat{s}\left[\frac{\dot{\epsilon}_p}{A}exp\left(\frac{Q}{RT}\right)\right]^n \tag{3}$$

The popularity of Anand's model in SMT modeling can be attributed to several factors: its inclusion as a standard material model in leading commercial finite-element programs [4], [5], early publications that detailed its use in modeling ball grid array (BGA) solder attachments [6], [7], and the reasonable correlation observed between test and simulation for a variety of BGA package designs [6], [8].

A literature survey was performed with the intent of providing, in condensed form, the readily available Anand parameters for solders used in the electronics field. Anand parameters for SnPb alloys are listed in Table II, while parameters for Pb-free alloys are in Table III.

Cautionary Note

Measurement of solder behavior and the generation of material constants are complicated tasks. The many choices regarding test specimen size and shape, specimen aging and storage conditions, specimen loading and constraints, and data capture and reduction will influence test results. The analyst is therefore encouraged to scrutinize the original sources before using these material parameters in their own simulation studies.

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TABLE I
DEFINITION OF ANAND MODEL PARAMETERS

symbol	description
s_0	initial value of deformation resistance
Q/R	Q: activation energy, R: universal gas constant
A	pre-exponential factor
ξ	stress multiplier
m	strain rate sensitivity of stress
h_0	hardening/softening constant
$\hat{s}$	coefficient for deformation resistance saturation value
n	strain rate sensitivity of saturation (deformation resistance) value
a	strain rate sensitivity of hardening or softening

TABLE II
ANAND PARAMETERS FOR SNPB ALLOYS

	ref.	s_0 (MPa)	Q/R (K)	A (1/s)	ξ	m	h_0 (MPa)	$\hat{s}$ (MPa)	n	a
97.5Pb2.5Sn	[6]	1.0	13330	2.2E8	0.203	0.1429	1E-9	1.0	1E-9	1.0
97.5Pb2.5Sn	[9]	15.09	15583	3.25E12	7	0.143	1787.02	72.73	0.00437	3.73
97Pb3Sn	[10], [11]	15.1	15600	3.25E4	7.00	0.0143	1790	72.7	0.00437	3.73
92.5Pb5Sn2.5Ag	[12], [13]	33.07	11010	1.052E5	7	0.241	1432	41.63	0.002	1.3
40Pb60Sn	[12], [9]	56.33	10830	1.49E7	11	0.303	2640.75	80.42	0.0231	1.34
37Pb63Sn	[14]	n/a	9400	1.09E7	0.07	0.316	2884	0.998	1.37E-5	1.26
36Pb62Sn2Ag	[14]	n/a	9400	8.49E6	0.065	0.322	2951	0.990	6.71E-4	1.33
36Pb62Sn2Ag	[12], [9]	42.32	11262	2.30E7	11	0.303	4121.31	80.79	0.0212	1.38
36Pb62Sn2Ag	[15]	12.41	9400	4.0E6	1.5	0.303	1379	13.79	0.07	1.3

TABLE III
ANAND PARAMETERS FOR PB-FREE ALLOYS

	ref.	s_0 (MPa)	Q/R (K)	A (1/s)	ξ	m	h_0 (MPa)	$\hat{s}$ (MPa)	n	a
98.5Sn1.0Ag0.5Cu	[16]	2.3479	8076	3.773	0.9951	0.4454	4507.5	3.5833	0.0120	2.1669
98.5Sn1.0Ag0.5Cu	[14]	n/a	8400	2.42E7	0.043	0.168	3162	1.005	8.10E-4	1.59
97.5Sn2.0Ag0.5Cu	[17], [18]	6.6	8500	500	4.3	0.16	6100	28.7	0.04	1.3
96.5Sn3.5Ag	[19]	$s_0(T)$	10278	177016	7	0.207	27782	52.4	0.0177	1.6
96.5Sn3.5Ag	[20]	7.17	29800	0.0034	2.48	0.03	2080	5.80	0.0068	1.41
96.5Sn3.5Ag	[20]	7.72	1.41E4	1.63E6	1.61	0.13	5.87E4	11.99	0.017	2.09
96.5Sn3.5Ag	[12], [9]	39.09	8900	2.23E4	6	0.182	3321.15	73.81	0.018	1.82
96.5Sn3.0Ag0.5Cu	[10], [11]	45.9	7460	5.87E6	2.00	0.0942	9350	58.3	0.015	1.50
tensile loaded										
96.5Sn3.0Ag0.5Cu	[21]	1.0665	10413.3	1.4283E8	1.472	0.141446	5023.9	20.2976	0.032472	1.120371
shear loaded										
96.5Sn3.0Ag0.5Cu	[22]	1.0665	10413.3	8.2465E7	2.550	0.141446	5023.9	20.2976	0.032472	1.120371
95.78Sn3.38Ag0.84Cu	[23]	7.2	83510	1.77E5	6.5	0.2046	4950	48.65	0.094	1.40
95.75Sn3.5Ag0.75Cu	[14]	n/a	8400	4.61E6	0.038	0.162	3090	1.04	4.60E-3	1.56
95.8Sn3.4Ag0.8Cu or										
95.5Sn4.0Ag0.5Cu	[17], [18]	1.3	9000	500	7.1	0.3	5900	39.4	0.03	1.4
95.5Sn4.0Ag0.5Cu	[24]	20	10561	325	10	0.32	8.0E5	42.1	0.02	2.57
95.5Sn3.8Ag0.7Cu	[25]	15.0	1.21E4	1.35E5	10.16	0.093	5.63E4	70.274	0.05	2.02
95.5Sn3.8Ag0.7Cu	[16]	3.2992	9883	15.773	1.0673	0.3686	1076.9	3.1505	0.0352	1.6832
95.5Sn3.8Ag0.7Cu	[20]	21.57	10041	9450.6	1.1452	0.1158	133.8025	13.3372	0.0402	0.1082
95.5Sn3.8Ag0.7Cu	[26]	37.1	6656	65.92	8	0.346	n/a	80.8	n/a	1.29
95.5Sn3.8Ag0.7Cu	[27]	39.5	8710	24300	5.8	0.183	3541.2	65.3	0.019	1.9
95.5Sn3.8Ag0.7Cu0.03Ce	[27]	28.5	8026	21200	5	0.130	4352.6	57.6	0.0175	2.3
100In	[28]	2.83E7	9369.7	2.33E8	49.97	0.2985	0.0	2.83E7	0.0	1.0

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