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Comparison of Creep Behavior of Lead & Lead Free Solders

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Abstract: With the ongoing concern regarding environmental pollutants, lead is being targeted in the electronic assembly arena. This highlights lead-free solders and the reliability test on SAC (Tin-Silver-Copper) compound. This compound has been selected as it has properties in par with the conventional lead solders. The main factor that is required for the complete substitution of the lead solders is the Creep test. This paper mainly concentrates on the Creep test of lead free solder in particular SAC compound. A 0805 resistor has been considered to simulate creep deformation and finally a detailed metallographic study has been performed. Virtual software called the ABAQUS 6.10 is used for finite element analysis. The characteristics of both lead and lead free soldering are compared.

Key words: environmental pollutants, lead-free solders, reliability test, thermal loads.

INTRODUCTION

Insight into the thermo-mechanical response of solder joints is critical to the design and deployment of reliable electronic circuit board assemblies. Understanding the mechanics of lead-free soldered assemblies is also essential to the development of accelerated test plans, predictive reliability models and to their use as effective tools for product reliability assessment. The life of Sn-Pb or lead-free solder joints is limited by the fatigue damage that accumulates in solder materials [1]. Accelerated testing provides distributions of failure times whose relevance to service life is determined by extrapolation to use conditions based on the appropriate Acceleration Factors (AFs). Since AFs are defined as the ratio of life under test and use conditions, their determination requires up-front predictions of solder joint lives under both sets of conditions. This paper aims at a quantitative review of the thermo-mechanical properties of lead-free solders, with emphasis on Sn-Ag-Cu (SAC) and Sn-Ag alloys. The Sn-Ag-Cu alloys of near-eutectic composition are labeled "SAC" throughout the paper. SAC solders are the alloys of choice for solder reflow assemblies. The quality of soldering and the solder are two crucial elements of the integrity of a solder joint, which is vital to the overall functioning of the assembly by itself [2]. Forming mechanical bonds, the shrinking interconnects size brings solder joint reliability to the forefront. Considering different operating conditions, the solder joints could experience various kinds of loading; this includes overstress, thermal cycling, vibration and shock, and cycle bending of circuit boards. As a result of every loading condition the solder may plastify, creep or rupture, the first two are considered as the principal deformation mechanisms in the solder joints [3]. The effect of each one is determined according to the operating condition, for example where the solder does not experience too much stress the role of creep is more important rather than plasticity. This especially happens when the package goes through a thermal cycle not a mechanical cycle like bending or shock, and the operating temperature is around or bigger than half of the melting temperature in absolute scale.

Solder interconnects are used to provide:

- Electrical connection between package and the substrate.
- Mechanical binding between package and substrate.
- Heat diffusion from the package.

Because the Coefficient of Thermal Expansion (CTE) are different between the package, ceramic or polymer, and substrate, tensile and/or shear strains occur in the solder interconnects when the device is powered on and heat is generated [4]. If the device is powered on and off, or the temperature of the environment fluctuates periodically, such heat induced tensile/shear strain within interconnects is as a result cyclic – causing thermo-mechanical creep failure.

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Literature Review:

The electronics industry in Europe is facing an impending change; a European Community Memorandum has been issued and it requires the use of Pb-free soldering materials instead of traditional Sn-Pb solders everywhere in the Community after July 1, 2006. The two main substitutes that are currently being considered are the eutectics, Sn-Ag [melting point (m.p. 221 °C)] and Sn-Ag-Cu (m.p. 217-219°C), with both melting points being higher than that of the n-Pb eutectic (m.p. 183 °C), and therefore both will require higher soldering temperatures for industrial applications. This justifies searching for substitute materials with properties closer to those of traditional solders.

Tin-Silver, Tin-Copper, and Tin-Silver-Copper (SAC) alloys have eutectics above 217°C but reflow can be performed at 235°C. They can form very large, asymmetric pasty zones for very small deviations from precise percentage composition, making them more susceptible to disturbed solder and other reflow process-related defects. This translates into open (cold) and/or high-resistance joints. The alloy is available at reasonable cost and the properties of this solder are promising.

The study about the Tin-Silver-Copper (SAC) alloys is minimal and this alloy has the properties in par with the conventional lead solders. Thus SAC alloy is being chosen for analysis and it is being compared with the later.

Why Lead Free?:

The reasons for expected innovations in lead free solders are;

1. Pending Legislation

WEEE Directive

Lead Tax Bill HR-2479

2. Liability Risk

Worker Exposure

End Product Disposal

3. Manufacturing Waste

Wave Soldering

Surface Mount

Hot Air Solder Coat

4. Water Treatment

OA Process Water

General Process Water

The study of lead-free solder has become a hot subject over the past few years. Government regulations are becoming more strict, and handling of waste materials are becoming more regulated. Now is the time to take a serious look at alternative materials for making electrical interconnections.

Due to potential litigation, liability risk is the primary reason for economic concern. If a worker is not properly monitored and is exposed to an elevated lead level, the lead could be carried home on his clothing, leading to contamination in the home, which is an area of concern and is a potential problem. The next concern is waste treatment in manufacturing. There are all types of wastes generated from a soldering operation: solder, solder dross, wipes and packaging containers. Some have a recycling value and others have to be disposed of as hazardous waste. On the process side, there are effluent wastes during cleaning, where solder balls and some heavy metal salts are washed off. In general, electronic manufacturing is a clean and safe environment to work in; however, governments still are targeting the removal of lead from solder, due to lead pollutants generated in other industries. The reason for the recent concern is that a great number of products are being disposed of in landfills, products such as televisions, radios, games and other products available to the consumer, and potential solder from these products is leaching into municipal water supplies.

Comparison Of Characters Of Lead Free Solders:

Applications For Lead Free Solder:

Surface mount technology (SMT) is a method for constructing electronic circuits in which the components (SMC or Surface Mounted Components) are mounted directly onto the surface of printed circuit boards (PCBs). Electronic devices so made are called surface mount devices or SMDs. In the industry it has largely replaced the through-hole technology construction method of fitting components with wire leads into holes in the circuit board. In particular 0805 and 0807 resistors are most commonly used in SMT, which is chosen for analysis.

Table 1: Comparison of characters of lead free solders

Characteristics	Comparison
Environmental impact	Nil
Availability	Higher than Sn/Pb
Melting temperatures	Higher than Sn/Pb
Thermal and electrical conductivity	Higher than Sn/Pb
Adequate joint strength	Higher than Sn/Pb
Thermal fatigue	Higher than Sn/Pb
Cost	Lesser among all SAC
Compatibility with existing processes	Similar to Sn/Pb
Printability and ease of soldering	Similar to Sn/Pb
Elongation	Lesser than Sn/Pb
Tensile strength	Higher than Sn/Pb
Shear strength	Higher than Sn/Pb
Creep strength	Higher than Sn/Pb
Fatigue resistance	Higher than Sn/Pb

Objectives:

- To perform the Creep test on two different compositions of lead free solders and a conventional lead solder.
- To compare the creep behavior of two different lead free solders with the conventional lead solder.
- To select a better composition among the two lead free solders and to proceed with further reliability analysis.

Methodology:

The Paper is preceded in the following procedure;

1. Initially the properties of lead free solders and the conventional Lead solders are studied.
2. The two lead free solders which have the properties similar to the lead solder is selected for analysis.
3. The two lead free solders SAC 1, SAC 2 and the conventional Sn-Pb solder is put on Reliability analysis.
4. Creep test is conducted on all the three compositions using software called ABAQUS 6.10.
5. The results are analyzed and the best composition of lead free solder is selected.

Reliability Analysis:

Creep and thermal behaviors are the two major factors which determine the reliability of a solder joint. This paper deals with creep analysis using ABAQUS software.

Creep Analysis:

Creep is a failure that occurs due to constant loading and constant temperature over a period of time. Creep test is performed for a constant temperature of about 105°C for approximately 200 hrs.

Three different solder compositions are chosen based on the advantages mentioned above and their properties and application are listed in table 2.

Solders Selected For Evaluation:

Table 2: The properties and applications of solder alloys

Solder alloys	Makeup (%)	Melting Point	Application
Tin/ Lead	63/37	183	Reflow and Wave soldering
Tin/Silver/Copper (SAC 1)	95.5/3.9/0.6	218	Reflow and Wave soldering
Tin/Silver/Copper (SAC 2)	95.5/3.6/0.9	218	Reflow soldering

Creep analysis is performed on all three compositions and the creep behavior of three compositions have been analyzed individually and their results have been compared to prove that lead free solder compositions are reliable than conventional lead solder using ABAQUS software package.

Finite Element Analysis:

Modeling is a useful tool used to supplement or replace accelerated tests, particularly in the early design states. Finite Element analysis is the method in which the body or structure is sub divided into smaller elements called finite elements. The properties of each type of finite element is obtained and assembled together and solved as a whole to get the solution. The modeling discussed here applies to creep induced ductile fracture only, and so will be suitable for modeling the damage that occurs due to typical thermal cycling of solder joints. For modeling creep deformation considering it as the most important damage mechanism influencing solder reliability due to thermal cycling loads, one of the frequently used packages (ABAQUS 6.10) has been chosen. The land pattern for a 0805 resistor is shown in fig 1

Fig. 1: A Typical 0805 Resistor with Solder Joint.

Part modeling:

Part module is used to build different parts of the model. So for convenience, divide the whole model into various parts and create each part using this module. Later all the parts can be assembled to form the entire model. Here, the model is divided into five parts - Ceramic, Cap, Solder, Copper and PC-Board.The modelling of solder is shown in fig 2 and fig 3. The actual dimension and geometry of the solder is taken from 0805 resistor solder joint and has been modelled.

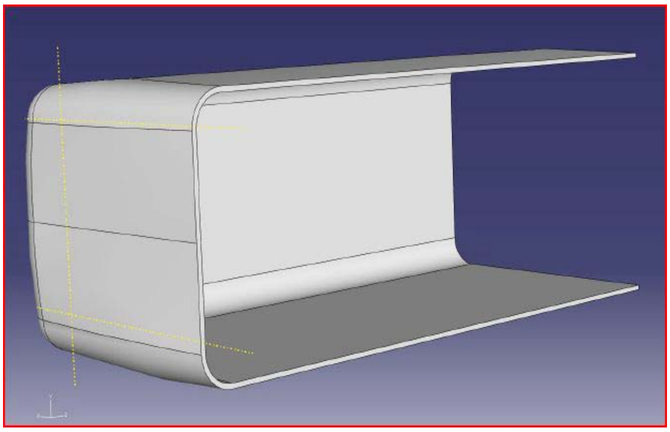

Fig. 2: A Completely Modelled Solder Cap

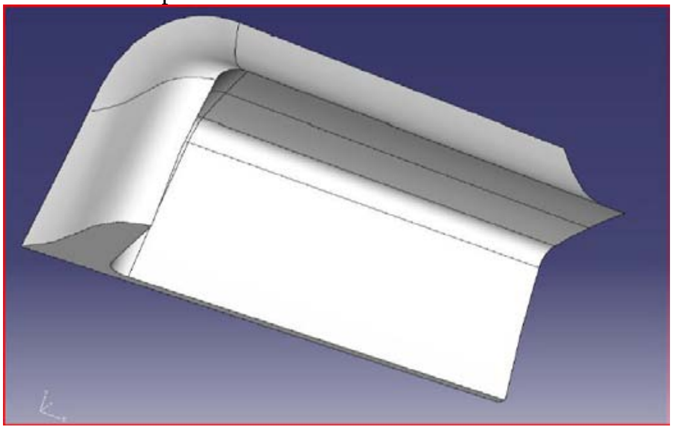

Fig. 3: A Completely modelled Solder Joint

Property Definition:

Property module is used to define properties of various materials used in the model. Then, sections are created and materials are assigned to each section.

For Ceramic material, Young's modulus is given as 220000Mpa, Poisson's ratio is 0.3 and the Expansion coefficient (α) is 8e-6.

For Cap material, Young's modulus is given as 120000Mpa, Poisson's ratio is 0.31 and the Expansion coefficient (α) is 1.6e-5.

For Solder, Young's modulus is given as 35000Mpa, Poisson's ratio is 0.34 and the Expansion coefficient (α) is 2.3e-5.

The creep law used for solder is the hyperbolic sine law and the law is

$$\varepsilon = C\, Sinh(\alpha\sigma)^{n}\, e^{-\frac{Q}{RT}} \quad (1)$$

Where ε is the strain rate, C is the power law multiplier, α is the hyperbolic law multiplier, n the stress order, Q the activation energy and R the universal gas constant. The values of these parameters are tabulated and shown in table 3.

Table 3: The values of constants in Creep law

Power law multiplier (/sec)	4.41e5
Hyperb law multiplier (/Mpa)	0.005
Eq Stress order	4.2
Activation Energy (J/mol/K)	4.5e4
Universal Gas Constant (J/mol/K)	8.314

For Copper material, Young's modulus is given as 90000Mpa, Poisson's ratio is 0.32 and the Expansion coefficient (α) is 1.65e-5.

For FR-4 PC board, Elastic Engineering constants, temperature and orthotropic Expansion values is included. And the values are shown in table 4.

Table 4: The value for FR – 4 PC Board

E1(Mpa)	E2(Mpa)	E3(Mpa)	Nu12	Nu13	Nu23
19300	8300	19300	0.4	0.15	0.4

G12(Mpa)	G13(Mpa)	G23(Mpa)	Temp(K)
8400	8400	8400	293

α 11	α22	α33
1.5e-5	8.4e-5	1.5e-5

Assembly:

In this module, all the parts created earlier can be put together (assembly) to get the required model. In the first step, the three major instances: Solder, Cap and Ceramic are assembled together as shown in fig 4.

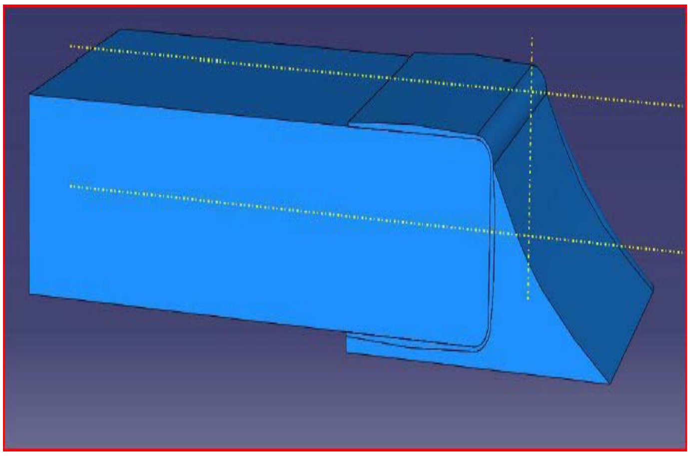

Fig. 4: Assembly of Solder with Solder Cap and Ceramic

The whole assembly of solder joint comprising of FR-4 PCB, Copper, Solder, Cap and Ceramic are made resembling the actual 0805 Resistor's Solder joint and is shown in fig 5.

Step:

This module is used to perform many tasks, mainly to create analysis steps and specify output requests. The steps are given for creep analysis to introduce continuous repeated load on the assembly.

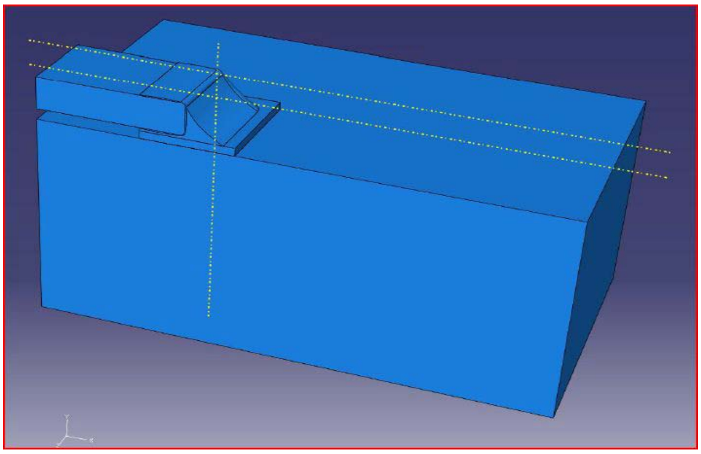

Fig. 5: Whole Assembly of 0805 Resistor Solder Joint.

Load:

Load module is used to define and manage various conditions like loads, boundary conditions and predefined fields.

Interaction:

As the name suggests, this module is used to define various interactions within the model or interactions between regions of the model and its surrounding. The interactions can be mechanical or/and thermal. Analysis constraints can also be applied between regions of the model.

Mesh:

This is one of the most important modules since accuracy of the results will depend on the meshing of the assemblies. This module can be used to generate meshes and even verify them.

Meshing is done for each component individually by specifying the required number of elements along its different edges. The mesh made on solder joint is shown in fig 6.

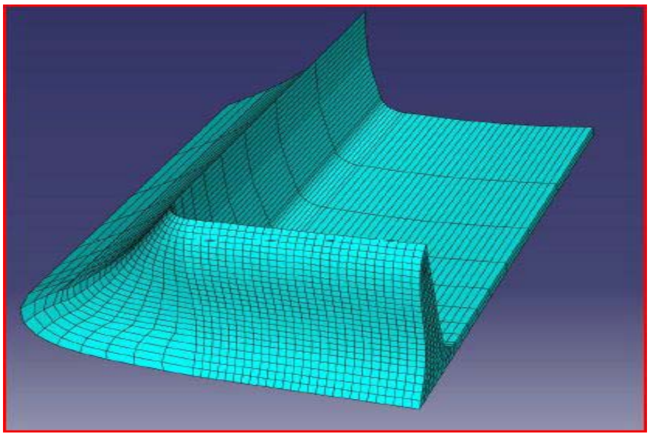

Fig. 6: Meshing of Solder Part.

The Standard Element Library is chosen with Linear Geometric Order – An 8 noded linear brick, reduced integration method (C3D8R). This is the default element type that is specified for 3 Dimensional elements and the mesh of the whole assembly is shown in fig 7.

Job:

Job module can be used to create and manage analysis jobs and submit them for analysis.

Post Processing:

The results generated from the analysis can be enormous so it requires additional processing which is termed post processing. Distribution of Von Mises Stress along the solder joint due to the above loading conditions is visible along the solder cap and solder joint and their value are shown in fig 8 and fig 9.

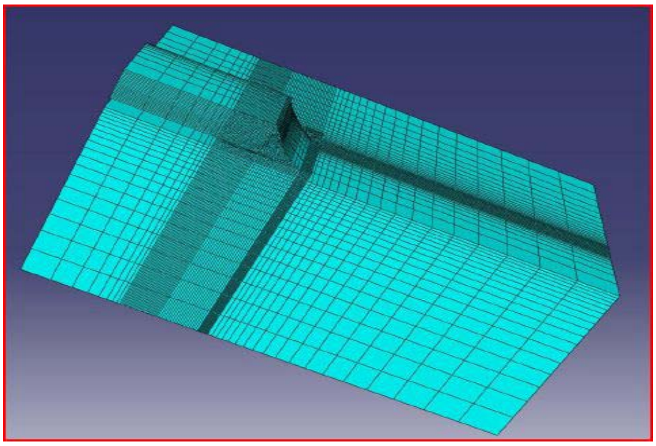

Fig. 7: Mesh of Whole assembly

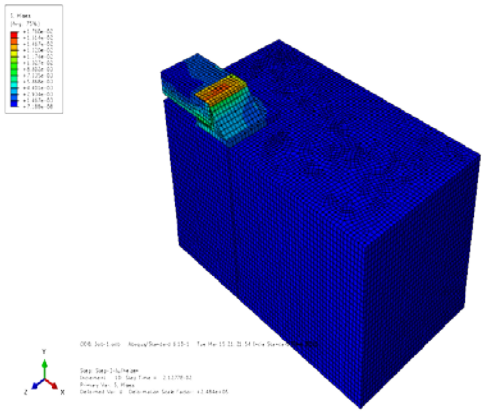

Fig. 8: Distribution of Von Mises Stress along the solder joint

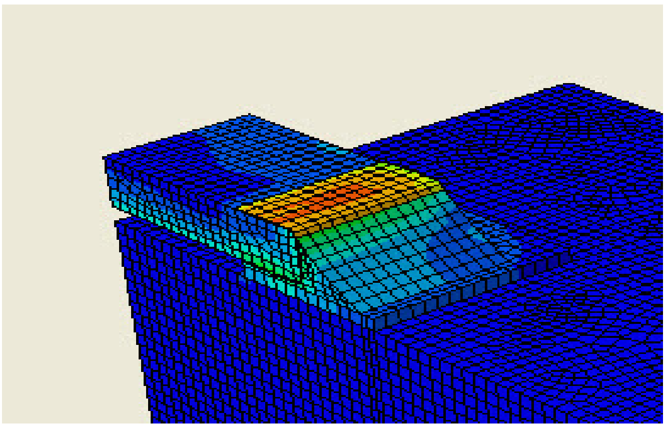

Fig. 9: Development of Von Mises stress due to creep loading.

Comparison Of Creep Behavior Of Lead And Lead Free Solders:

Creep behavior of solder over time is plotted for steady state creep conditions for two compositions of SAC and conventional Sn-Pb solder and the result has been shown in fig 10.

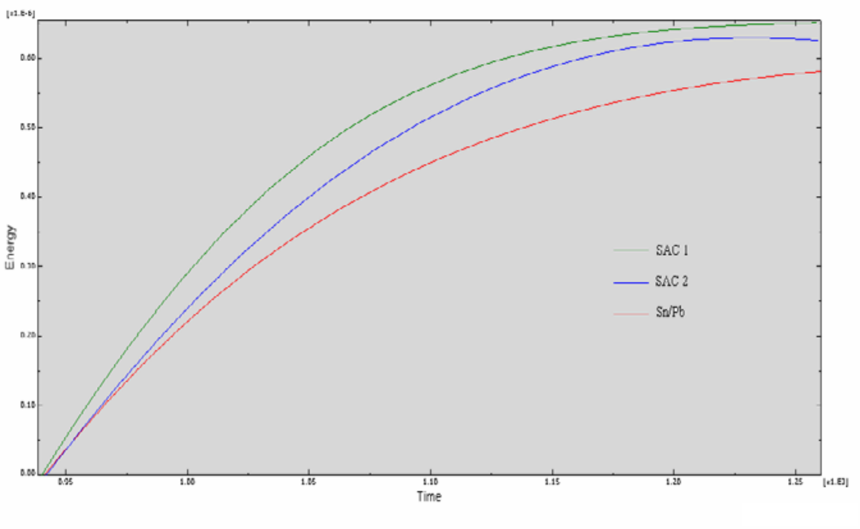

Fig. 10: Comparison of Creep Behavior of Lead and Lead Free solders.

Inference

- Creep analysis has been performed for SAC 1, SAC 2 and Sn/Pb compositions and their strain energy with respect to time have been plotted.
- It is evident from the graph that, SAC 2 possesses higher strain energy than conventional Sn-Pb composition and SAC 1 possess much higher strain energy than both SAC 2 and Sn-Pb.

The steady state creep rate is predicted and the creep rate Vs Stress graph is plotted for the two compositions of SAC and it is compared with the conventional Lead solder. They are stressed below 30 Mpa and the results are obtained.

This has been analyzed for two temperatures 60 C and 95 C and the results are shown in fig 11 and fig 12.

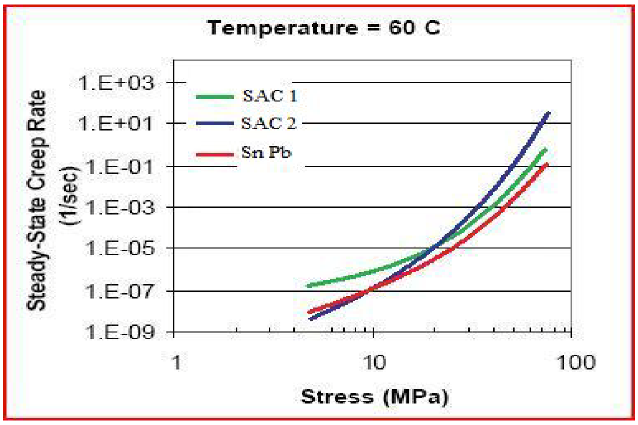

Fig. 11: Creep Vs Stress graph for 60 C

Creep Rate Definition:

Creep Rate is defined as the time rate of deformation of a material subject to stress at a constant temperature. Creep rate is inversely proportional to deformation of the component. It is evident from the graph that the creep rate of lead free solders are much higher than tin lead solders, in particular SAC 2 compositions has better creep rate than SAC 1 and Sn-Pb compositions. And it is noted that at higher stress the creep rate of the solder increases than the Sn-Pb solder.

Therefore SAC solders have a higher life. Therefore it is concluded that SAC 2 composition can be a substitute for the conventional lead solders. The steady state creep rate prediction shows that the SAC solder can be stressed more than the conventional lead solders. And also it can be seen that the SAC solders diverges at high stresses.

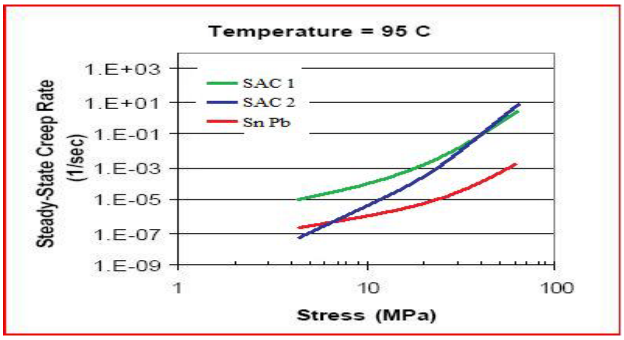

Fig. 12: Creep Vs Stress graph for 95 C

Inference

- The graph depicts that lead free solders are better than lead solders. In here two different lead free solder compositions are tested and in these two SAC 2 composition shows better results when compared to other.

From the above two graphs, it is concluded that the SAC 2 has yield the better results than SAC1 and Sn-Pb solders

Conclusion:

- The Creep test is performed on two different compositions of lead free solders SAC 1 and SAC 2and their results have been compared with the conventional Sn-Pb solder using ABAQUS software package.
- It is evident from the graph that the creep rate of lead free solders are much higher than tin lead solders, in particular SAC 2 compositions has better creep rate than SAC 1 and Sn-Pb compositions.
- SAC 2 has been selected to be the better composition among the two lead free solders.

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Using finite element analysis for simulation of reliability tests on solder joints in microelectronic packaging, Department of Civil, Structural and Environmental Engineering, SUNY at Bu€alo, 212 Ketter Hall, Buffalo, NY, USA, HKS ABAQUS Inc., Detroit, MI, USA