Methods for analyzing the reliability of mounting microelectronic radio components

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Abstract. According to modern standards of the radio-electronic industry, manufacturers have to use more and more lead-free technology for soldering nodal joints in produced electronic equipment for various purposes. But with the use of lead-free solders, the question arose about their reliability in comparison with their lead counterparts. It is just about the study of the reliability of lead-free solders that is described in this article. For these purposes, such brands of lead-free solders were investigated as SAC 0107, SAC 0307, SAC 0807, SAC 105, SAC 263, SAC 305, SAC 405, SAC 387, SAC 396. The main differences between linear regression analyses of the reliability of lead-free solder based on the characteristics of the solder and under the influence of thermal cycles based on the Weibull distribution are substantiated. The results of the research are presented at the end of the article in the form of graphical figures and tables.

1. Introduction

With the advent of the RoHS directive, electronics companies are forced to limit the amount of lead in their hardware. The recommendation is moving towards the use of lead-free solders in PCBs. A serious question remains whether lead-free solder is so reliable for all products, especially those that work in harsh conditions or are designed to solve important problems. When product reliability is the main quality, the transition to lead-free technology must begin with the choice of materials, designs and manufacturing to ensure reliability. Key aspects include the principles of basic science, practical global manufacturing, reference test data and criteria for reliable performance. This analysis is intended to assess the reliability of lead-free solder using a linear regression model and Weibull distribution, which are detailed in [1, 2, 3].

The integrity of the solder joint, in addition to operating conditions, design and configuration, is also influenced by the internal properties of the solder. This paper examines the relationship between such properties of the solder as wettability (contact with the base), melting point and tensile strength, as well as their influence on the reliability of the solder. To assess the reliability of a soldered joint, when considering the soldering process itself, it is very important to know the characteristics of the solder. Considering the most popular SAC family of lead-free solders, great attention should be paid to the effect of silver on the quality of the joints. SAC solders are very popular in the industry lately. The abbreviation SAC comes from the first letters of the elements Sn, Ag, Cu found in solder alloys. Solders differ in the ratio of the proportions of Sn, Ag and Cu and are divided into several groups. Table 1 lists some of the most popular SAC alloys used in the industry and their properties.
Table 1. Comparative characteristics of some SAC solders

| Lead free alloy | Composition          | Solidus temperature, °C | Temperatur e °C | Density (g/cm³) | Tensile strength at break g/cm² |
|-----------------|----------------------|-------------------------|-----------------|-----------------|-------------------------------|
| SAC 0107        | Sn99.2Ag0.1Cu0.7     | 217                     | 228             | 7.32            | 320                           |
| SAC 0307        | Sn99Ag0.3Cu0.7       | 217                     | 228             | 7.33            | 300                           |
| SAC 0807        | Sn98.5Ag0.8Cu0.7     | 216                     | 225             | 7.33            | 310                           |
| SAC 105         | Sn98.5Ag1.0Cu0.5     | 215                     | 227             | 7.32            | 400                           |
| SAC 263         | Sn97.1Ag2.6Cu0.3     | 217                     | 224             | 7.36            | 430                           |
| SAC 305         | Sn96.5Ag3.0Cu0.5     | 217                     | 220             | 7.38            | 500                           |
| SAC 405         | Sn95.5Ag4.0Cu0.5     | 217                     | 220             | 7.44            | 530                           |
| SAC 387         | Sn95.5Ag3.8Cu0.7     | 217                     | 220             | 7.44            | 600                           |
| SAC 396         | Sn95.5Ag3.9Cu0.6     | 217                     | 220             | 7.44            | 620                           |

The most common solder used in the industry is the SAC305 alloy; it is most widely used in wave soldering technology, as it has good wetting and joint strength.

2. Effect of silver on lead-free solder properties

Silver has been used in solders for many years in both tin-lead and lead-free technologies. It plays a really important role in solder joints and improves their properties, for example, the use of silver in the alloy allows it to lower its melting point. Much research has been done on the solidus and liquidus melting points for an alloy with the addition of silver [4]. This indicates that an increase in the mass fraction of silver in the alloy leads to a decrease in the melting point in a certain range. As shown in Figure 1, as long as the mass percentage of silver is less than 4% of the total alloy, the melting point of the liquid in the alloy decreases.

![Figure 1. The melting point of the alloy SAC](image)

It can also be seen in Figure 2 that an increase in the mass fraction of silver to 1.5% in the alloy sharply reduces the melting point of the solder. When the mass fraction of silver in the alloy is more than 0.3%, the melting point is 217 to 227 °C, which meets the requirements of reflow soldering and lead-free wave soldering.
Analyzing table 1, one can notice some regularity associated with the mechanical properties of SAC solders, so in the seventh column of this table there is an increase in the tensile strength of the alloy with an increase in the silver content. The silver content affects the Ag3Sn intermetallic compound. The formation of an intermetallic compound and the size of the crystal grain of Sn were investigated in [5]. Dispersion curing of the Ag3Sn intermetallic compound leads to a high tensile strength. The stress-strain dependences shown in Figure 3 for different brazing alloys show the effect of silver content on tensile strength, on rupture.

The advantages of using silver include the fact that its use improves the wetting of the alloy. Wetting is a very important property of the solder, as the function of the alloy is to make a good bond to hard surfaces. The wettability of solders is an important alloy property that directly affects the integrity of the solder joints.

This property is very important when using soldering processes such as wave soldering or reflow soldering. In [5], the duration of wetting and the maximum wetting ability were measured for the alloys SAC305, Sn0.7Cu and SAC0307. Five no-clean fluxes were used to study the wetting characteristics of these alloys. The optimum balance of silver in the alloy helps to reduce the surface
tension of solders at standard operating temperatures. Lower surface tension results in better wetting performance. Comparison of wetting duration and wetting ability by wetting balance method is shown in Figure 4.

![Figure 4. Comparison of wetting duration and wetting ability](image)

Considering the presented characteristics, it is possible to reveal some relationship between the intrinsic properties of the solder and the silver content in the alloy. First, analyzing Figure 1, you can see that when the mass fraction of silver is equal to 0.3%, the graph begins to grow; the effective amount of silver is in the range from 0.3 to 1.5%, and the maximum concentration at which the melting point is most effective and has a constant value equal to 4%. Second, in the seventh column of Table 1, there is an increase in the tensile strength of the alloy with an increase in the silver content, until the concentration reaches a value of 3.9%. A further increase in the mass fraction of silver sharply reduces the strength of the alloy and negatively affects its characteristics. Third, studying the diagram in Figure 4, it can be seen that with an increase in the mass fraction of silver to 3%, the wetting ability indicators improve, and the results are already declining by 4%. From all of the above, we can conclude that the proportion of silver in the alloy equal to 3% is the most optimal result for all three parameters. And in practice we observe this in the SAC305 solder, in which the silver index is 3, and therefore this alloy is considered the best lead-free solder used in the wave soldering and reflow soldering industry.

3. Regression analysis of the reliability of lead-free solder under thermal cycling using the Weibull distribution

To carry out a quantitative analysis of all the processes occurring in the RES, in which it may be necessary to assess the reliability of devices based on lead-free solder, this work considers the process of thermal cycling. To assess the reliability of lead-free solder, a method for predicting the service life of the solder is presented, which is based on the Weibull regression model [1,2]. The ready-made data presented in table 2 [6] are used as input data.

| IST 6 PCCX230C RT/CT = 0.6 | RF0 6 PCCX230C RT/CT = 0.5 |
|---------------------------|---------------------------|
| 235                       | 240                       | 240                       |
| 287                       | 344                       | 243                       |
| 331                       | 247                       | 318                       |
| 135                       | 149                       | 196                       |
| 317                       | 163                       | 142                       |
| 349                       | 202                       | 211                       |
| 302                       | 210                       | 254                       |
| 198                       | 144                       | 310                       |
| 216                       | 208                       | 279                       |
| 179                       | 167                       | 485                       |

Table 2. Data after thermal cycles
Table 2 presents data on thermal cycles depending on the method of heat pretreatment. We suppose that the failure rate is distributed according to Weibull’s law with a shape parameter $k$ and a scale parameter $\lambda$. We suppose that only the shape parameter $k$ is strongly material-dependent, and the scale parameter is related to the energy absorbed by the test coupons during thermal testing. $\lambda$ represents the characteristic lifetime tested samples. In [7], since the lead-free alloy is the same for each test, the difference between manufacturers and thermal cycle methods is considered as a factor influencing the shape parameter $k$. In this study, the difference between manufacturers and the energy absorbed by test coupons can affect the scale parameter. The test used two different heat treatment methods: IST and Reflow. Ramp temperature, ramp time, cool down time and total cycle time are different. Main issue is the quantitative analysis of energy. Based on the research in [7], the energy absorbed by the test specimens during thermal testing can be calculated using the following equation:

$$\text{Energy} = \text{PCC} \cdot \Delta T \cdot \frac{RT}{CT}$$

where PCC – cycle times of the preconditioning process; $\Delta T$ – temperature range between ramping temperature and cooling temperature; RT – ramp time; CT – total cycle time;

To assess reliability, it is necessary to obtain a linear regression formula for the shape parameter and the scale parameter.

4. Reliability analysis

The linear regression model for evaluating lead-free solder reliability for wettability, strength and melting point parameters is as follows. 1. Let us construct normal line graphs and select sections on them that can be described by equations of straight lines.

![Figure 5](image1.png)

**Figure 5.** Normalized graph of the dependence of the melting temperature on the mass fraction of silver with a step of 0.1.

![Figure 6](image2.png)

**Figure 6.** Normalized graph of the dependence of the ultimate strength on the mass fraction of silver with a step of 0.1
Let us find the equations of straight lines with the corresponding domain of definition for each such section. For melting point:

\[
Y_1(x) = \begin{cases} 
-5x + 230.5, & 0 \leq x \leq 1.5 \\
23, & x > 1.5 
\end{cases} 
\]

(2)

\[
Y_2(x) = \begin{cases} 
-100x + 370, & 0 \leq x \leq 0.3 \\
88x + 273.3, & 0.3 \leq x \leq 3.9 \\
-90x + 971, & 3.9 \leq x \leq 4 
\end{cases} 
\]

(3)

\[
Y_3(x) = \begin{cases} 
-100x + 260, & 0 \leq x \leq 0.3 \\
18.52x + 284.4, & 0.3 \leq x \leq 3 \\
-30x + 430, & 3 \leq x 
\end{cases} 
\]

(4)

Let's get the final schedule of reliability assessment:

\[
Y(x) = \begin{cases} 
0.4x, & 0 \leq x \leq 1.5 \\
0.153x + 0.391, & 1.5 \leq x \leq 2.9 \\
0.05x + 0.705, & 2.9 \leq x \leq 3.9 \\
0.1x + 1.29, & 3.9 \leq x \leq 4 
\end{cases} 
\]

(5)

To check the obtained data, we construct a regression model of the Weibull distribution:
Linear regression for shape parameter:

\[ k = a_0 + a_1 s_1 + a_2 s_2 + a_3 s_3 + a_4 r \]  

Linear regression for scale parameter:

\[ \ln(\lambda) = \beta_0 + \beta_1 s_1 + \beta_2 s_2 + \beta_3 s_3 + \beta_4 \ln(n) + \beta_5 r \]  

After the research carried out, the following conclusions can be drawn: First, analyzing the data obtained, one can notice a regularity that the reliability of lead-free solder has a direct proportional dependence on the value of the mass fraction of silver in the alloy under study, and reaches its best values at 3% silver content. These values experimentally confirm the previously derived patterns presented in the article. Second, after analyzing Figures 8 and 9, one can make sure that the values obtained as a result of reliability analysis using a linear regression model coincide with the values obtained by modeling the Weibull distribution, from this it follows that the calculations performed are correct.
5. Conclusion
In this article, 2 types of analysis were considered, so the linear regression analysis of the reliability of lead-free SAC solder based on the characteristics of the solder shows good simulation results, the obtained model can be used to assess the quality of the solder depending on the mass fraction of silver in the alloy. Regression analysis of the reliability of lead-free solder under thermal cycling shows good model convergence. The Weibull distribution model builds on WinBUGS Bayesian inference with a meta-analysis of test data from previous studies to further explore the failure cycle of lead-free solder joints during thermal testing. IST and reflow are two types of preprocessing processes used in the test. The Weibull distribution model simulates the characteristic service life test pieces with three independent variables: component suppliers, type of pretreatment process and energy absorbed by the samples. The model is flexible and easily adapts to any such situation. Since lead-free solder is very important for the electronics and electrical industries, it can be used with any electronic device such as laptops, desktops, smartphones, etc. Many electronic devices have fans to cool their components, making them a "real" thermal cycle for printed circuit boards in devices. Different devices have different thermal cycle conditions and cycle times. To predict the life of the hardware when using lead-free technology in such conditions, a similar Weibull distribution model can be used by changing some parameters and previous distributions of the model to correct specific situations.

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