

Decision Matrix as a Tool for Pb-Free Alloy Selection

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Abstract

For aerospace products, there is no current legislation or directive that sets a schedule for transitioning to Pb-free electronics, however, aerospace industry is likely to be “swept along” because its dependency on the larger commercial electronic industry which has already changed its materials, components, and assemblies to Pb-free. In this study we present a synthesis of Pb-free solders along with critical factors affecting its selection and deployment. A decision matrix methodology is introduced as a valuable tool to assist the alloy selection process based on specific criteria and life cycle conditions.

Keywords: *Pb-free; SAC; Reliability; Solder alloys; Decision matrix*

Introduction

The use of lead (Pb) has been widely accepted in the electronic industry in the form of the ubiquitous eutectic Sn-Pb solder to attach discrete components to printed circuit boards (PCB's). These attachments are not only mechanical, but also serve as the electrical interconnection between the device and the PCB. Approximately 5 million tons of Pb are consumed annually on a global basis, of which batteries represent the largest single application in terms of Pb consumption (~81%). Solders for electronic assemblies account for about 0.5% of the consumption [1]. Although storage batteries constitute the largest percentage of consumption, the alleged near 100% recycling practice have exempt them from the ban. However, there has been a

European Union (EU) mandate to eliminate Pb from electronic products starting July 1, 2006. Some useful standards related to Pb-free practice are listed below in Table 1. As a result of these legislations, the electronic industry in general and specially the DoD and defense contractors are actively searching for Pb-free solder alternatives for the microelectronics assembly process. However, because no single Pb-free solder is likely to qualify for all defense applications, it is critical to assess and validate alternative solders for the particular applications.

The primary goal of this paper is to provide a documented Pb-free solder assessment and to present the Decision Matrix as a suitable selection tool.

Table 1. Useful standards related to Pb-free technology [2].

Standard	Subject
Association of Connecting Electronics Industries, IPC-J-STD-006	Detailed list of both Sn-Pb and Pb-free solders
IPC-J-STD-002, 003	Board and component lead solderability
MIL-M-38510	Plating thickness for good component lead solderability.
GEIA-STD-0005-1	Performance Standard for Aerospace and High Performance Electronic Systems Containing Pb-free Solder.
JEDEC J-STD-620A	Plastic package moisture sensitivity, heat tolerance

Approach

Pb-free solders must conform to a broad range of properties and characteristics to be considered as suitable candidates to replace Sn-Pb solders for use in electronic assemblies [3]. Pb-free solder candidates must be compatible with product packaging trends of increasing densification and portability. Solder joints of high performance electronic packages are expected to withstand increasing mechanical, electrical, and thermal burdens that can lead to reduced reliability and failures under field conditions [4]. There are two basic requirements that all solder interconnection must satisfy [5]. First, they must wet and bond to metallic terminals of features on components and substrates. This implies that the solder must be capable of forming intermetallic compounds (metallurgical bonds) with Cu, Ni, and other metals routinely utilized in electronic packaging. Second, a solder must have a melting point that is sufficiently low to be reflowed as a paste to attach components, yet high enough to avoid re-melting (or any ill effect associated with pasty range) due to operating conditions in the field.

This investigation was conducted following a two steps approach. The first step focused on the survey of potential alternatives. As a result of this phase a preliminary alternatives list was compiled. The selection parameters are discussed later in the article. The second step was the rating of the pre-selected alternatives from step one. The rating procedure followed the “criteria rating and weighted ranking” procedure also known as Decision Matrix [6], in which each solder alternative was evaluated based on a set of critical characteristics. Selection of critical parameters along with weighting factors is discussed in details in the following sections.

Preliminary Alternatives

Many of the Pb-free solder alloys of interest consist of minor additions of third or fourth elements to binary alloy systems to achieve a desired benefit such as enhance wettability, reliability, melting temperature, and microstructure. What follows is a description of the selection criteria.

Supply and Abundance:

The number of viable elements to replace Pb is reduced when factoring in the condition of sufficient abundance and availability. Availability pertains to the quantity that is produced, whereas abundance refers to world reserves in Earth’s crust. To illustrate the criticality of supply and abundance, it can be deduced from available data [7], that Bi, Au, In, or Ag will not be viable replacement for Pb. This is based on cost and world reserves of metals; reserves

imply that in addition to abundance, the metal can be economically extracted by current technologies.

Cost:

Because Pb is one of the least expensive elements on Earth, any substitute will have an impact on cost; mainly because it is likely that the substitutes will contain Sn, Ag, Cu, and In. If either In or Ag is used, their content must be low due to the cost impact as well as their supply problem [2].

Melting Temperature and Range:

The melting point of elements Ag, Cu, Ni, and Au are too high to serve as base materials and some are too expensive as well. These two conditions (namely melting temperature and cost) leaves In and Sn as sole alternatives for base metal, but In is quite expensive when compared to Sn that added to In availability issues. That leaves Sn, whose solder alloy melting points are typically between 170°C and 280°C [2], therefore providing a suitable baseline for Pb-free solder alternatives to eutectic Sn-Pb. To be compatible with standard surface mount process, and to avoid PCB and component damage requires a solder alloy melting point not higher than about 230°C, whereas application conditions may be as broad as -55°C to 150°C. This implies a minimum melting point of at least 175°C to avoid re-melting [4]. As a result of this temperature window limitation Sn metal must be alloyed with other elements in order to lower its melting temperature. Eutectic alloys with either Cu or Ag have melting points too close to pure Sn, so only a few percent of these elements can be added to Sn before the melting temperature gets to unacceptable levels [3]. Alloying elements used with Sn for potential alternatives are Cu, Ag, Bi, Sb, Ni, and In. These elements have been selected because they tend to reduce the melting temperature of the alloy and possess desirable mechanical, electrical, and thermal properties [8].

The compositions of Pb-free solder alloys and their corresponding melting temperatures are readily available in the open literature [1,2,8,9]. It is important to understand that a solder alloy with a discrete melting temperature is desired (i.e. eutectic composition). However, if it is not possible, the melting range ($T_L - T_S$, where T_L refers to the liquidus temperature and T_S is the solidus) should not be more than 10°C, preferentially below 5°C. Alloys with a wide melting range (pasty range) are known to be susceptible to hot cracking during solidification (fillet lifting), therefore eutectic or near-eutectic composition alloys are desired.

Wettability:

Solder wettability is the capability of an alloy in the molten state to spread over the solid surface of another metal. It is the precursor of solderability which describes the solder's ability to form a solder joint. All high-Sn solder alloys exhibit a higher surface tension and are more chemically aggressive (i.e. exhibit greater tendency to form intermetallic compounds with termination pad metallization) when compared to eutectic Sn-Pb [10]. Pb has the effect of lowering the surface tension of Sn-Pb solders which results in enhanced solderability. None of the elemental additions made to Sn duplicates the effects of Pb in terms of lowering surface tension, therefore it explains the observable poor wettability of Pb-free alloys.

Metallurgical complexity and resulting physical and mechanical properties:

It is generally agreed upon that none of the Pb-free binary systems investigated is likely to be a consensus replacement of eutectic Sn-Pb, due to higher melting temperatures, poor wettability, and higher costs, just to mention but a few reasons. Viable candidates typically consist of a small quantity of a third or fourth element added to a binary

alloy. The alternative selection will depend on specific application and life cycle conditions. There are an increasing number of applications that require significantly enhanced mechanical properties. For example, the operating temperature range for telecommunications electronics products normally can span from -55°C to 100°C. There are critical applications such as avionics and defense products that can experience thermal cycles that can span from -55°C to 165°C and higher in addition to shock and vibration conditions.

Alloying elements have other effects in addition to affecting the melting temperature of the system. Both Cu and Ag have a low solubility in Sn, therefore they tend to form intermetallic compounds so there is little opportunity for solid solution strengthening. The elements Zn, Bi, and In all exhibit good solid solubility in Sn, thus they contribute to strengthening the Sn matrix. However, they must be introduced carefully because they tend to form low melting point alloys which are too low for electronic applications [11].

Candidate List:

After performing a comprehensive survey across the open literature, a preliminary alternatives list has been compiled and presented in Table 2.

Table 2. Preliminary list of Pb-free alloys.

Alternative Alloys	(wt. %)	Melting Point (°C)
Sn / Pb (baseline)	63Sn – 37Pb	183 (eutectic)
Sn / Cu	99.3Sn – 0.7Cu	227 (eutectic)
Sn / Cu / Ni	99.2Sn – 0.7Cu – 0.05Ni	227 (eutectic)
Sn / Ag	96.2Sn – 3.8Ag	221 (eutectic)
Sn / Ag / Cu	95.8Sn – 3.5Ag – 0.7Cu	217 (eutectic)
	96.5Sn – 3.0Ag – 0.5Cu	217-220
	95.5Sn – 3.8Ag – 0.7Cu	217 (eutectic)
	98.5Sn – 1.0Ag – 0.5Cu	215 - 227
	95.5Sn – 4.0Ag – 0.5Cu	217 - 219
Sn / Ag / In	95Sn – 3.5Ag – 1.5In	218 - 223
Sn / Ag / Bi	91.8Sn – 3.4Ag – 4.8Bi	200 - 216
Sn / Ag / Cu / Bi	93.3Sn – 3.1Ag – 0.5Cu – 3.1Bi	209 - 212
	92.3Sn – 3.4Ag – 1.0Cu – 3.3Bi	205 - 214
Sn / Ag / Cu / Sb	96.2Sn – 2.5Ag – 0.8Cu – 0.5Sb	213 - 218
Sn / Ag / Cu / Sb / Bi	91.8Sn – 4.6Ag – 1.6Cu – 1Sb – 1Bi	214 - 220

Selection parameters which included material properties, manufacturability, reliability, cost, and availability (as already discussed) were used for this

initial reduction from the over 70 alloys listed in NIST database [9] to the ones listed in Table 2.

Rating of Potential Pb-free Alternatives

As can be observed from the previous section, the leading candidates are binary and ternary alloys based on the Sn-Cu and Sn-Ag alloy systems, in near-eutectic and alloyed forms. This includes a class of eutectic and near-eutectic Sn-Ag-Cu (SAC) alloys that provide acceptable combinations of properties. Yet no alloy can be considered a direct replacement in terms of critical properties for the Sn-Pb system, and process compromises are made most notably in terms of increased soldering temperature. Candidate replacement alloys include binary, ternary, and quaternary alloys of Sn with Ag, Zn, In, Sb, and Cu. In order to provide an objective rating among these alternatives, a Decision Matrix, based on a criterion rating form and weighted ranking, has been used [6]. In this technique, the alternatives (solder alloys) were judged against critical requirements such as cost, availability, melting temperature, wettability, mechanical properties, physical properties, reliability, and fatigue resistance. These requirements are the so called decision criteria. The relative importance (weight) of each criterion was assigned based on available information in literature. For the method to be successful, the total sum of the assigned weights must equal 100. Each alternative was rated against each criterion; the rating scheme was based on a scale from one (low) to ten (high). The final score was calculated by multiplication of the weight for each alternative by the rating followed by the summation of these values. The best alternative is the one with the highest score according to this ranking scheme.

Melting Temperature:

Among the critical qualities, melting temperature is of great importance, primarily due to its effect in manufacturability and process compatibility. The higher the melting point of the solder alloy, the higher the processing temperature during the reflow operation which may introduce the necessity for new board materials as well as devices. Based on this fact a weight of 15 points has been assigned to melting temperature. The closer the melting temperature of the alloy under consideration gets to 183°C (melting of Sn-Pb benchmark) the better, therefore a score of 10 will be assigned to low melting alloys, whereas a score of 1 will imply a high melting point system. Cost and availability will also influence the final decision regarding alloy selection, for this instance a weight of 15 has been assigned. Information on material cost is readily available in literature [2], hence the scoring has been assigned based on the relative cost of the proposed alternatives against that of standard eutectic Sn-Pb. In this case a 10 will be

for Sn-Pb and lower values will correspond to more expensive alternatives.

Reliability:

The reliability of a solder alloy is very sensitive to the electronic package itself; it is well known that surface finish of the PCB as well as that in the leads of the components have a great impact on the microstructure of the solder joint. The ability of an alloy to absorb plastic deformation is dependant on the interfacial reactions and resulting structure. Reliability is the most critical parameter since it refers to the ability of a system to render its intended function under specific life cycle conditions for a period of time. Reliability testing is often difficult and requires accelerated testing. The whole assembly including package type, metallization, geometry, are factors that affect the outcome of the test. For this assessment we have not performed any specific reliability tests, therefore reliability data (based on mean cycles to failure) was used to rank the possible alternatives. In terms of weight, reliability has received the highest relative importance, i.e. 25. In order to assign a score, data from multiple references was used. During this exercise a ten refers to systems with the longest life, whereas a 1 indicates those with shorter cycles to failure, or lack of data due to known reliability limitations.

Wetting:

The formation of a reliable joint depends on good wetting between the solder material and the work pieces (board and lead terminal). Wetting must take place in order to allow the solder alloy to interact and bond to the pad and component. The mechanics of wetting depend upon the surface energies of the materials involved during the reaction. Surface energy is a function of temperature and varies for each alloy, therefore a comparison of surface tension of Pb-free alloys may provide insights of which system could perform better in a manufacturing environment. Although it is difficult to draw universal conclusions from the results of different investigators, it has been shown that most of the Pb-free alloy systems can be expected not to perform as well as the standard 63Sn37Pb alloy (this is based on the fact that lower alloy surface tension and lower contact angle implies better wetting). In addition, it can be generally say that Zn alloys do not perform as well as other Pb-free systems. Loomans et al. [14] systematically investigated alloying effects on several potential substitute alloys and eutectic systems. Results from his experiments showed that additions of 1% (by wt.) of Zn or In degraded wetting characteristics. However, Loomans concluded that

flux characteristics were more important than alloying constituents for enhancing solderability of Pb-free systems. The overall statement is that the poorer wetting characteristics of most Pb-free solders can be overcome by the flux system, leading to adequate joint formation for assemblies with typical lead finishes. In general, increasing temperature improves the wetting characteristics of all solder alloys on copper, provided enough flux activity is available. The variations among alloys, and the temperature effects, emphasize the importance of optimizing the reflow profile for the selected alloy. The reflow profile must balance the limitations of the flux, the maximum temperature of the materials comprising the assembly and the wetting characteristics of the alloy. As has been discussed in previous sections, SnAgCu (SAC) alloys have emerged as the preferred alloys for replacement of SnPb. Bukat et al. [14] have presented data for various SAC alloys compared to SnPb and SnAg.

Based on the criticality of wetting, it has been assigned a 15 in the weighting scale. For the rating exercise a ten indicates a surface tension (or wetting angle) close to that of eutectic SnPb, whereas a 1 corresponds to a solder alloy with a relatively high surface tension or poor wetting characteristics.

Understanding the monotonic behavior of Pb-free solders is of paramount importance in the selection of suitable alternatives. The tensile properties and time dependent creep and stress relaxation behavior form the basis for comparisons of alloys. Generally, the monotonic tensile properties of metals placed in engineering service are described by the familiar stress-strain curve. However, solders are complex, given their high homologous temperatures and strain rate dependencies. It is important to note that bulk properties of solders obtained from the standard tensile test, and actual joint properties, can vary significantly due to size and microstructural effects [16]. Therefore, the type of testing conducted on the alloy is important when examining data to compare alloys. In addition, monotonic properties are affected by temperature, strain rate and microstructure. There is a competing effect between joint strength and ductility; enhancing the strength of the alloy results in decreasing ductility and vice versa, hence a tradeoff approach must be used.

Generally, in the case of cyclic life in fatigue (low cycle) ductility is more important (strain governed behavior), whereas strength may be more important in cyclic regimes with smaller strains (high cycle fatigue). Based on this knowledge a weight of 10 has been assigned to mechanical properties. The rating will assume that ductility (percent elongation) is more critical than strength; therefore a 10 will correspond to a higher ductility while a one (1) will indicate a less ductile alloy.

Fatigue in solder alloys is a complex process of interaction between deformation mechanisms driven by plastic deformation and creep (time / temperature dependent) deformation that occur during cycling loading of the solder joints. This complex damage process is called creep fatigue [12]. Electronic equipment placed in service will be subject to cyclic loads, the severity of this loading is a major factor in defining the life-time of the product. For the most part, electronic equipment experiences cyclic loading from changing temperatures in the environment or due to power dissipation. These temperature changes result in cyclic loading of the solder joints. Repeated deformation of the joints results in the accumulation of fatigue damage which is the ultimate failure mechanism of solder joints, hence affecting its reliability. Fatigue resistance of solder alloys is then of paramount importance for the selection of suitable alloys. This criticality becomes evident by the assignment of a 15 to its weight. Rating solder alloys in terms of fatigue resistance is not trivial, many factors such as loading cycle, temperature limits, mean temperature, holding time, are known to have great impact on fatigue life.

Rating Results

What follows is a documented attempt to rank the alternatives according to the criteria defined in the previous section. Possible Pb-free alloys have been ranked against each criterion based on available data, at the end, an educated, objective ranking should result that will serve as a basis for selection. The first criterion of interest is the cost associated with the substitution of eutectic Sn-Pb. Table 3 gives the relative cost of selected Pb-free solders based on their densities [17,18,19].

Table 3. Relative cost and rating of some candidate Pb-free solders to replace eutectic Sn-Pb.

Alloy	Metal Cost (US\$/lb.)	Metal Cost (US\$/in³)	Percent increase cost/in³ compared to Sn-Pb (%)	Rating (1-10)
Sn – 37Pb	2.37	0.75	0	10
Sn – 0.7Cu	3.48	0.92	23	9
Sn – 0.7Cu – 0.05Ni	3.48	0.92	23	9
Sn – 3.8Ag	6.32	2.33	125	4
Sn – 3.8Ag – 0.7Cu	5.90	1.58	110	6
Sn – 4.0Ag – 0.5Cu	5.92	1.59	110	6
Sn – 4.0Ag – 1Cu	5.92	1.59	110	6
Sn – 3.5Ag – 1.5In	8.15	2.18	190	1
Sn – 3.4Ag – 4.8Bi	6.24	1.7	125	4
Sn-2.5Ag-0.8Cu-0.5Sb	5.48	1.46	95	7
Sn-2.0Ag-0.5Cu-7.5Bi	5.09	1.39	85	8

To be compatible with standard surface mount and wave soldering processes and to avoid PCB and component damage require a solder alloy melting temperature not higher than about 230°C, hence any alternative close to this threshold will be rated close to one (1). Application temperatures for electronic devices may be as broad as -55°C to 150°C, implying that a minimal melting of at least 175°C is required. Table 4 provides the rating of suitable lead free alloys based on melting temperature.

The reliability aspects of solder alloys will be discussed together with the fatigue data since both are closely interrelated. In our effort to provide a documented assessment of possible Pb-free alternatives some critical caveats must be discussed. First of all, under accelerated test conditions where temperature extremes are elevated and cyclic hold time shortened, results from different investigators have varied significantly with test conditions [20,21,22,23]. Therefore comparing alloys at one cyclic condition, without controlling other critical variables, may not be very meaningful. In fact, given the significantly different material behavior and current incomplete knowledge of fatigue behavior, it is difficult to draw conclusions as to the reliability of those solder joints in a product. However, an attempt has been made here in order to provide an objective assessment of Pb-free alloys considering the limitations of the available data. As a first step we have ruled out those alternatives that have been identified as poor performers by the vast majority of researchers in the field. We first started with Bi containing alloys which have demonstrated to suffer from segregation and cracking problems as well as the formation of low melting phases in the presence of Pb-traces. Therefore a very low ranking has been assigned to those alloys. Alloys with In additions have also been associated with low melting point

phases [12] as well as with inferior mechanical properties. A major drawback of In is its cost and availability, hence low scores have been assigned to those alloys as well. Quaternary or higher order alloys are very difficult to control, therefore not much data is available in the open literature. The lack of reliability data for these complex systems is a problem for this assessment, thus a low rating has been assigned in lieu of lacking information. For most surface mount application, Sn-Ag-Cu (SAC) alloys are leading replacement candidates for eutectic Sn-Pb. In general, these alloys (SAC family) with higher melting temperature also tend to have higher strength, lower ductility, and greater creep resistance. Intuitively, we may expect that for similar cyclic conditions, SAC would perform better than other alloys due to their superior creep properties and the higher homologous temperature. However, in typical life cycle conditions for electronic assemblies, plastic deformation may play a crucial role in cyclic damage, therefore, lower ductility may offset improved creep resistance. This is why a new family of SAC solders with smaller amounts of Ag (i.e. SAC 105 and SAC 101) [23,24] are under investigation. It has been demonstrated [25] that as Ag content goes down strength, hardness, and modulus decreases steadily; but ductility is enhanced. This improved ductility may result in a more compliant (energy absorbent) solder, therefore improving fatigue life. Another approach has been the elimination of Ag and the accompanying disappearance of the Ag₃Sn platelets within the bulk solder structure [23]. This needle shaped phase embedded in the Sn-matrix is responsible for higher mechanical strength but it is also responsible for the reduced ductility. The Sn-Cu-Ni (SCN) alloy is mostly comprised of a near 100% soft β -matrix [23] which acts as a compliant material that has demonstrated excellent fatigue life.

Main constitutional phases in the SAC systems are the β -Sn and Ag_3Sn , which is present as a needle

shaped phase. Main constitutional phase of SCN is almost 100% Sn.

Table 4. Rating of Pb-free alternatives based on melting temperature.

Alternative Alloys	(wt. %)	Melting Point (°C)	Rating (1-10)
Sn / Pb (baseline)	63Sn – 37Pb	183 (eutectic)	10
Sn / Cu	99.3Sn – 0.7Cu	227 (eutectic)	3
Sn / Cu / Ni	99.2Sn – 0.7Cu – 0.05Ni	227 (eutectic)	3
Sn / Ag	96.2Sn – 3.8Ag	221 (eutectic)	4
Sn / Ag / Cu	95.8Sn – 3.5Ag – 0.7Cu	217 (eutectic)	7
	96.5Sn – 3.0Ag – 0.5Cu	217-220	5
	95.5Sn – 3.8Ag – 0.7Cu	217 (eutectic)	7
	98.5Sn – 1.0Ag – 0.5Cu	215 - 227	4
	95.5Sn – 4.0Ag – 0.5Cu	217 - 219	6
Sn / Ag / In	95Sn – 3.5Ag – 1.5In	218 - 223	5
Sn / Ag / Bi	91.8Sn – 3.4Ag – 4.8Bi	200 - 216	8
Sn / Ag / Cu / Bi	93.3Sn – 3.1Ag – 0.5Cu – 3.1Bi	209 - 212	7
	92.3Sn – 3.4Ag – 1.0Cu – 3.3Bi	205 - 214	7
Sn / Ag / Cu / Sb	96.2Sn – 2.5Ag – 0.8Cu – 0.5Sb	213 - 218	6
Sn / Ag / Cu / Sb / Bi	91.8Sn – 4.6Ag – 1.6Cu – 1Sb – 1Bi	214 - 220	5

Single Alloy Suggestion

Overall, as reported by Dasgupta et al. [22], based on a comparison between eutectic Sn-Pb, Sn-Ag, and Sn-Ag-Cu, SAC, alloy Sn-3.9Ag-0.6Cu outperformed the other alternatives. However, there is still more work to be done specifically focusing on Sn-Cu-Ni and lower Ag content SAC's.

Summary Results from Alloy Comparison

To summarize our effort during this Pb-free solder assessment a Decision Matrix (Table 5) is provided below:

Table 5. Decision Matrix for selected Pb-free alternatives.

Criteria	Weight	Alternatives				
		SnPb	SAC (Family)	SnCuNi	SnAg	SnAgCuBi
Melting Temperature	15	10 [150]	6 [90]	3 [45]	4 [60]	7 [105]
Cost	15	10 [150]	6 [90]	9 [135]	6 [90]	8 [120]
Reliability	25	7 [175]	8 [200]	9 [225]	7 [175]	5 [125]
Wettability	15	10 [150]	5 [75]	6 [90]	4 [60]	8 [120]
Mechanical Properties	10	6 [60]	9 [90]	4 [40]	9 [90]	5 [50]
Physical Properties	5	5 [25]	8 [40]	7 [35]	9 [45]	6 [30]
Fatigue Resistance	15	7 [105]	8 [120]	8 [120]	7 [105]	9 [135]
Total		815	705	690	625	685

Discussion

From this exercise it can be observed (based on total score) that indeed eutectic Sn-Pb obtained the highest score, which confirms the fact that no replacement has yet been found. However, by inspection of the scoring sheet it can be concluded that the SAC system(s) is currently the preferred system on an overall basis. It is worth noting that the SAC column (Table 5) groups the family of these ternary alloys, thus these results represent the average rather than the specifics of a particular composition. As will be discussed later, modifying the composition of these systems (SAC's) may yield different results. Of particular interest are the reduction of silver and the accompanying elimination of the Ag₃Sn platelets, which could lead to enhanced reliability in shock and vibration environments. Another crucial outcome from this assessment is the relatively high score of the Sn-Cu-Ni system. Based on these results, Sn-Cu-Ni must be further studied owing to the fact that it could be a suitable alternative for shock and vibration conditions [23]. It is worth noting that this Decision Matrix is an open working tool that the scientific community, as well as practitioners could use to rank the alternatives based on specific applications, therefore, results in Table 5 are not pretended to be

absolute but a representation of the usefulness of this approach.

Conclusion

Decision matrix methodology has been successfully introduced as a valuable, flexible, and objective tool to assist in the Pb-free alloy selection process. This method was demonstrated to serve as a working tool that could be tailored to multiple segments of the electronic industry by selection of pertinent criteria as well as rating values according to specific life cycle conditions and criticality of the application. Despite recent efforts, there still not a drop-in replacement for eutectic Sn-Pb solder for electronic assemblies. In summary, as of today, the most recommended Pb-free alloy on an overall basis is the Sn-3.8Ag-0.7Cu eutectic, but particular life cycle conditions must be carefully considered before making a final recommendation.

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