The current status of lead-free soldering

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Lead-free solder mounting technology took off in the Japanese market during the year 2000, and as the year 2001 ushered in the 21st century, a large number of products with lead-free solder mounting were already appearing on store shelves. Elsewhere, EU deliberation on the draft of the WEEE/RoHS directive moved into the home stretch, and was scheduled for final approval by vote in the EU assembly in April 2002. The course had been set for adopting lead-free solder for surface processes of parts as well, bringing the possibility of lead-free solder mounting very close to achievement. This article will provide a view of the current state of technological progress in lead-free soldering, both in Japan and abroad, and will discuss future prospects for the technology.

1. *Introduction*

Environmentally friendly technologies found within the industries at the forefront of the age of electronics and automobiles are destined to become one of the key facets of technology for the new era. Many of the products that have been created within these fields have contributed to the affluence of human life, but at the same time have carried substances with a very high environmental load stemming from energy consumption and the discharge of noxious substances into the environment. To counter these problems, the home appliance recycling law has been enforced in Japan since April 2001. As recycling has just begun, it will take some time to determine the effects produced. However, there have already been reports in the news of an increase in illegal dumping, and concern has surfaced regarding the lack of arrangements in the social systems surrounding recycling. Besides these four types of home appliances, every year a massive amount of discarded electrical appliances is accumulating within the narrow confines of this country. Considering this situation, rather than looking for foreign models for environmentally friendly products, we must create our own models right here. If leading-edge industries are to maintain their position at the forefront of the next century, they must not be content to merely offer individual products incorporating outstanding functions. The real key to their success will be their ability to reduce the environmental load.

2. *Regulatory trends for leaded solder*

Legal regulations on leaded solder began in 1990 with the United States “Lead Exposure Reduction Act S2637 and S729.” The proposals in these bills created a sudden burst of interest worldwide in developing lead-free solder. Movements to develop lead-free solder went forward in the US under the NCMS Lead-Free Soldering Project 1) (NCMS: National Center for Manufacturing Sciences, 1994-1997), and in the EU under the IDEALS Project 2), (BRITE/EURAM 95/1994; Improved Design Life and Environmentally Aware Manufacturing of Electronics Assemblies by Lead-Free Soldering, 1996-1999). In Japan, this movement was connected to the inauguration of the Lead-free Soldering Research Council (1994 to present) within the Japan Institute of Printed Circuits (currently, the JIEP: the Japan Institute of Electronics Packaging). While America has recently moved away from legislating the changeover to lead-free solder due to technological difficulties, EU has included the adoption of lead-free solder in the movement to legislate disposal of all electronic products in its proposal for WEEE (Waste Electrical and Electronic Equipment 3)). The final draft of the WEEE directive (June 2000) deals separately with recycling (in WEEE) and hazardous waste in RoHS (Restriction of the use of Certain Hazardous Substances in Electrical and Electric Waste). This draft proposed regulating lead in solder in 2008, but in May 2001, the EU assembly voted to move up the target date to 2006. The EU assembly will deliberate the draft of this directive once more before a final vote in April 2002.

Within the EU, Denmark and Sweden are separately studying their own legislation. Denmark had already enacted a law at the end of the year 2000, but the item of “electrical parts” is excepted. These “electrical parts” are thought to include all mountings. Sweden is studying a long-term plan to eliminate the use of all lead by the year 2020. However, the laws of both countries have been influenced by the enactment of WEEE/RoHS.

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In Japan, though, the subject of legislation to regulate lead solder has not yet been taken up. However, control of lead is being strengthened through such means as review of the water quality standards concerning lead, strengthening amendments to the Waste Disposal Law, and the enactment in April 2000 of the home appliance recycling law originating in 1998. Unless electronic devices containing lead are disposed of properly, they can no longer be discarded.

3. *Global lead-free solder development project*

In the US, as soon as lead-free solder legislation was proposed, the lead-free solder project headed by the NCMS initiated research and development of lead-free solder in a program lasting four years. The achievements of the project have been made available in a database, and offer information on such matters as modifying equipment, and processes for selecting alternative materials.1)

The project initially selected for study 79 types of alloys considered at the time to be potential candidates for use in lead-free solder. Basic attributes considered included toxicity, resource availability, economic feasibility, and wetting characteristics. The selection process narrowed the field down to the final 7 alloys shown in Table 1, and these received secondary evaluation for reliability and ease of mounting manufacturing. Evaluation of the individual alloys did not result in the final selection of a single candidate, but Table 2 discusses 3 alloys that could be recommended as candidates. Screening comments indicated that the eutectic alloy Sn-58Bi was not suitable for use as standard solder due to the scarcity of Bi resources. However, since this material can be used for mounting at less then 200°C, and has chalked up a 20-year plus record of use in mainframes, this solder was deemed suitable for special applications.

These results were used to construct a database on lead-free solder that includes the information in these tables along with other items such as (1) recommended applications for lead-free solder, (2) alloy composition guidelines reflecting price and availability, (3) database of the 7 selected alloys and comparison with Sn-Pb eutectic alloy, (4) data on the characteristics of the other 70 eliminated alloys, (5) optimal process conditions using various test PCBs, (6) strength evaluation and metallurgical reaction analysis for the selected alloys and various surface mounting process reactions, (7) predicted life (using NCMS Project proprietary life prediction software) and thermal fatigue evaluation for 4 of the selected alloys, and (8) assessment of non-toxicity and alloy composition.

After the NCMS Project had finished, the move to legislate the use of lead-free solder was terminated, and research fervor cooled. However, Japanese progress in practical applications combined with EU legislation gave impetus to the creation of a Task Force under the auspices of NEMI (The National Electronics Manufacturing Initiative). The NEMI Task Force was organized in May 1999 to handle lead-free mounting. The major objectives of this group's activities are as follows.

(1) Obtain the capacity for manufacturing lead-free products in 2001 with a view to eliminating all lead in 2004.
(2) Clarify the parts, materials, and process conditions that can be used for lead-free solder mounting.
(3) Select a single main candidate from the Sn-Ag-Cu family of solder.
(4) Obtain cooperation of the various manufacturers of parts, materials, and equipment to confirm the smooth transition to high-temperature mounting to maximum temperatures around 260°C.
(5) Establish evaluation standards for lead-free processes.

Table 1 The final 7 lead-free solder candidates determined by the NCMS project

Code	Composition	Melting point (°C)
A1	Sn-37Pb (relative alloy)	183
A4	Sn-3.5Ag	221
A6	Sn-58Bi	139
E4	Sn-3Ag-2Bi	220
F2	Sn-2.6Ag-0.8Cu-0.5Sb	211
F17	Sn-3.4Ag-4.8Bi	210
F21	Sn-2.8Ag-20In	187
F27	Sn-3.5Ag-0.5Cu-1Zn	221

Table 2 NCMS Project recommended 3 alloys for surface mounting

Alloy	Liquidus Solidus	Range of application	Comments
Sn-58Bi	139°C (Eutectic)	General home appliance products Cell phones	Possible to mount at low temperatures. Has eutectic composition, but doesn't stand up to heat well. For surface mounting, superior to Sn-Pb in thermal fatigue characteristics. For use in through holes, better than Sn-Pb for CPGA-84 (84-pin Pin grid array), but not as good for CDIP-20 (20-pin Dual inline package).
Sn-3.5Ag -4.8Bi	210°C 205°C	General home appliance products Cell phones Space and aviation Automotive	In the 0°C to 100°C range, superior to Sn-Pb eutectic solder for surface mounting. In the –55° to +125°C range, better than Sn-Pb In wave soldering, lift-off almost always generated.
Sn-3.5Ag	221°C (Eutectic)	General home appliance products Cell phones Space and aviation Automotive	For surface mounting, equivalent to Sn-Pb from 0 to 100°C, but not as good from –55 to +125°C. Has less lift-off occurrence than other high Sn alloys. Reliability of Sn-2.6Ag-0.8Cu-0.5Sb is still not clear.

This project carried out research on process and material conditions for lead-free mounting from the point of view of such items as reflow soldering, wave soldering, wash, and repair. Companies such as Celestica, Compaq, Delphi/Delco, HP, Motorola, Intel, IBM, NIST, Nortel Networks, Solectron, Visteon, and others participated in the activities. In addition, NEMI along with groups such as EIA, IPC, and JEDEC cooperated on duplicating the contents of those activities, performing investigative research and carrying out experimental development. The project was completed in January 2002, and we have heard that mass production items had been developed.

In the EU, the IDEALS Project was carried out from May 1996 to April 1999 with the participation of companies such as Philips and Siemens. The two main objectives of the project were to clarify the process window (range for process conditions such as thermal profiles) and to confirm reliability in practical use for alloys such as Sn-Ag-Cu, Sn-Ag-Bi, and Sn-Cu. Simultaneously, they also developed VOC-free flux. In the area of reparability, flux-containing Sn-Ag-Cu and Sn-3.5Ag had absolutely no problems, and the project was able to confirm the viability of both manual and automatic repairs.

The main conclusions of the IDEALS Project can be summarized as follows.

(1) The practical application of lead-free solder is technically and industrially feasible.
(2) Sn-Ag-Cu(-Sb) alloys can be used in a wide range of applications.
(3) The process window for wave soldering is roughly the same as for conventional solder.
(4) VOC-free flux has been developed.
(5) The process window for reflow soldering is compatible with most parts, but problems occur in one sector, from 225°C to 230°C.
(6) Sufficient reliability can be attained.

In addition to completing the project, Philips succeeded in bringing to mass production from the end of 1999 an Sn-Ag-Bi single-side wave soldering PCB for lighting utensils (Fig. 1), and announced that it had already delivered one million units by March 2000.

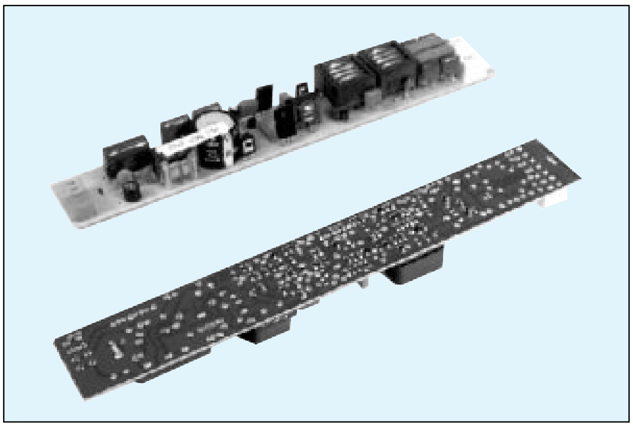

Fig. 1 Electrical lighting PCB created by Philips
(from Mr. Co Van Veen)
<Single-side wave soldering using Sn-Ag-Bi solder>

4. Japanese domestic projects

In March 2000, two years of research were completed on “Research and Development for the Standardization of Lead-free Solder” supported by NEDO as a Japanese national project.$^{4)}$ Evaluation and development were carried out by two working groups, JEIDA (Japanese Electronic Industries Development Association [currently JEITA*]) and JWES (The Japan Welding Engineering Society) under the auspices of the NEDO organization through the Japan Environmental Management Association for Industry. The main role undertaken by the JWES working group was in regard to evaluating material characteristics for lead-free solder candidate materials and investigating standard evaluation methods. The main role assumed by JEIDA was concerned with mounting characteristics and reliability evaluation with the aim of promoting practical application. JEIDA also cooperated with EIAJ (Electronic Industries Association of Japan, currently JEITA) in evaluating compatibility of various electronic parts and evaluating lead-free surface processes. Table 3 shows a list of solder alloys investigated by JEIDA.

Table 3 Solder alloys evaluated in periods 1 and 2 by the JEIDA group

Alloy		First period	Second period	R/W*
Sn-Ag	Sn-3.5Ag-0.75Cu	○	○	R & W
Sn-Cu	Sn-0.7Cu-0.3Ag		○	W
Sn-Ag-Bi	Sn-2Ag-3Bi-0.75Cu	○	○	R
	Sn-2Ag-4Bi-0.5Cu-0.1Ge	○		R
	Sn-3.5Ag-5Bi-0.7Cu	○		R
	Sn-3.5Ag-6Bi	○	○	R
Sn-Bi	Sn-57Bi-1Ag		○	R

***R: Reflow soldering**
W: Wave soldering

The following items sum up the JEIDA input.

Overall

(1) Grasped the various characteristics of lead-free solder. Any type of solder has some limitations, but all are feasible for practical application.

Reflow soldering

(2) There are no significant problems with migration or insulation characteristics, but wettability is somewhat inferior to Sn-Pb eutectic solder.
(3) The greater the amount of Bi in the alloy, the worse the compatibility with Pb.

Wave soldering

(4) Lift-off generation is accelerated by the presence of Bi quantities, but lift-off may occur even without Bi, depending upon the conditions.
(5) Lead-free solder is superior to Sn-Pb eutectic solder in regard to creep and temperature cycles.

A number of new projects were initiated during 2000 and 2001. One of those was the IMS project “Developing environmentally friendly next-generation joining technology” headed by Hitachi, Ltd. The project was

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* JEITA (Japan Electronics and Information Technology Industries Association) is a body inaugurated in November 2000 by combining JEIDA (Japan Electronic Industries Development Association) and EIAJ (Electronic Industries Association of Japan).

budgeted by the Ministry of Economy, Trade and Industry, and in the year 2000 participants included Hitachi Ltd., Sony Corp., Sharp Corp., Oki Electric Industry Co., Ltd., and other universities and national research laboratories. In 2001, the organization was expanded even further. This project targets technological evaluation of lead-free solder regarding reliability and mounting characteristics, clarifying the biological impact of the component elements, and also establishing high-level mounting technology that will be safe and environmentally friendly into the future.

Plans call for initiating a project within the year under the title of "Standardization of necessary test methods for solder connections that reduce the environmental load." The project is budgeted by the Ministry of Economy, Trade and Industry, and led by the JWES welding group. As can be seen from the title, the project targets standardization of test methods. Meanwhile, JEITA has initiated a project to standardize mounting evaluation from the parts aspect.

The JIEP (Japan Institute of Electronics Packaging) initiated the "Low-temperature lead-free solder development project" as a two-year plan to intensively investigate solder capable of low-temperature mounting, and the year 2002 is the final year of the project. Since this project intersects the research activity of JIEP, items include solder materials, of course, as well as most other items related to mounting, such as PCB materials and design, electromagnetic design, electronic parts processes, mounting equipment, and test methods, and future aims extend to presenting available specifications to all persons involved in lead-free mounting as well as constructing various databases. The low-temperature project is striving for mounting temperatures below those of current Sn-Pb eutectic solder, and so includes materials such as Sn-Zn and Sn-Bi as candidates. The first symposium was held in March 2001, and a report on Sn-Zn has been published[5)] and the final report will be released in summer 2002.

5. The current status of applying lead-free solder

The major Japanese electronics manufacturers lead the world in mass production that incorporates lead-free solder. Table 4 shows the roadmaps of the individual companies toward adopting lead-free solder and presents some examples of applications. However, this table represents the range of information available to at the time of writing, so please understand that some areas may be overlooked.

Table 4 Major objectives of each manufacturer (above the dotted line) and mass production product application (below the dotted line)

Manufacturer	Items targeted	Time period	Comments
Matsushita Electric Industrial Co., Ltd.	Eliminate all lead	End of 2002	
	Applied to compact MD players Applied to cassette players Applied to VCRs	Oct 1998 Jan 2000 End of 1999	Reflow soldering: Sn-Ag-Bi-In Wave soldering: Sn-Cu(-Ni)
NEC Corporation	Reduce 1997 volume by half Eliminate all lead	Mar 2001 Dec 2002	At least 1 product per department (Mainly Sn-Ag-Cu)
	Applied to pagers (beepers) Applied to Note PCs	Dec 1998 Oct 1999	Reflow soldering: Sn-Ag-Cu Nitrogen reflow soldering: Sn-8Zn-3Bi
Hitachi, Ltd.	Reduce 1997 volume by half	Mar 2002	Achieve 50% reduction in domestic production
	Eliminate all lead in in-house manufacturing	Mar 2002	Except products manufactured overseas and externally purchased parts.
	Eliminate all lead in Hitachi Group	Mar 2004	
	Applied partially to camcorders and refrigerators	Feb, Oct 1999	Wave soldering: Sn-Ag-Cu
	Applied to vacuum cleaners, washing machines, and air conditioners	From 2000	
	Applied to Note PCs	From 2000	Reflow soldering + halogen-free PCBs
Sony Corporation	Eliminate all lead	2005	
	Applied to camcorders Applied to TVs, Note PCs	Mar 2000 Oct 2000	Sn-2.5Ag-1Bi-0.5Cu Wave soldering + halogen-free PCBs
Toshiba Corporation	Applied to main products Used in all products	2000 2003	
	Applied to TVs, refrigerators, washing machines, home laundry, cleaners, etc.	Dec 2000	Insertion mounting
Mitsubishi Electric Corporation	Reduce volume by half Eliminate all lead	2004 2005	4 home appliance products
Fujitsu Limited.	Adopt lead-free for all LSI Adopt lead-free for half of PWB Eliminate all lead	Oct 2000 Dec 2001 Dec 2002	
Nissan Motor Co., Ltd.	Applied to keyless entry systems	Aug 2000	Wave soldering: Sn-Ag-Cu
Royal Philips Electronics	Applied to electric lighting PCBs	Dec 1999	Wave soldering: Sn-1Ag-5Bi
Ericsson Inc.	Adopt lead-free for 80% of new products, & halogen-free PCBs	2002	
	Applied to cell phones	2001	Sn-Ag-Cu
Ford Motor Company	Applied to vehicle anti-theft devices and transceiver modules	Dec 2000	Not yet announced
Motorola, Inc.	Applied to cell phones	Dec 2002	Reflow soldering: Sn-Ag-Cu

The world's first mass-produced product incorporating lead-free solder was the Matsushita compact MD player in the autumn of 1998 (Fig. 2). Produced using Sn-Ag-Bi-In solder batch reflow soldering, by mid-2000 the process had become fourth-generation and had expanded to products such as cassette players and was being used in overseas manufacturing.

Matsushita Electric Industrial Co., Ltd. began mass production of VCRs from the end of 1999 using wave soldering of single-sided PCBs with Sn-Cu(-Ni) solder.

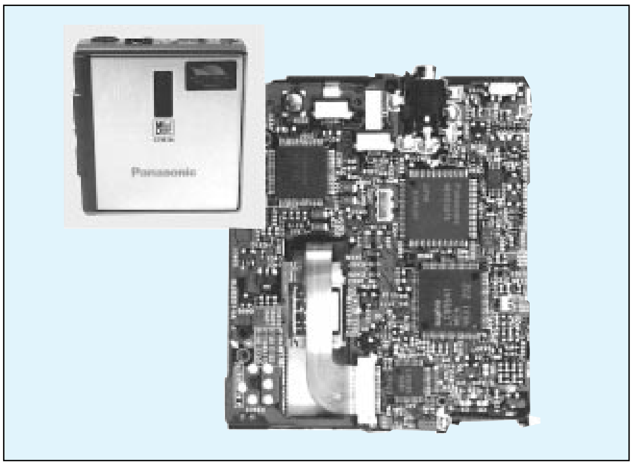

Fig. 2 Matsushita compact MD and its PCB
The world's first mass-produced lead-free device
(from Matsushita Electric Industrial Co., Ltd)

NEC Corporation began using Sn-Ag-Cu solder to manufacture pagers (beepers) from the end of 1998. In October 1999, thanks to better wettability yielding an improved flux, the company began manufacturing note PCs using Sn-Zn-Bi solder, and is now applying this solder to other types of PCs. NEC Corporation is using Au and Ni plating on PCBs, and using nitrogen reflow soldering in manufacturing. Fig. 3 shows a picture of those PCBs.

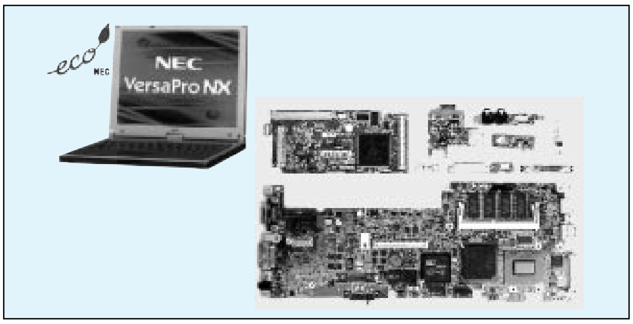

Fig. 3 NEC note PC and its PCB
Manufactured using Sn-8Zn-3Bi reflow soldering
(from NEC Corporation)

Hitachi, Ltd. has been actively promoting the changeover to lead-free solder since 1999, and has announced that approximately half of the products it manufactures in Japan were using lead-free solder by mid-2000. Fig. 4 shows the main PCB of a refrigerator, mass-produced using single-side wave soldering with a high-temperature system solder. The company is performing reflow soldering for note PCs with Sn-Ag-Cu solder, and is not only using lead-free solder but has also changed over to halogen-free PCBs. Fig. 5 shows one of these PCBs.

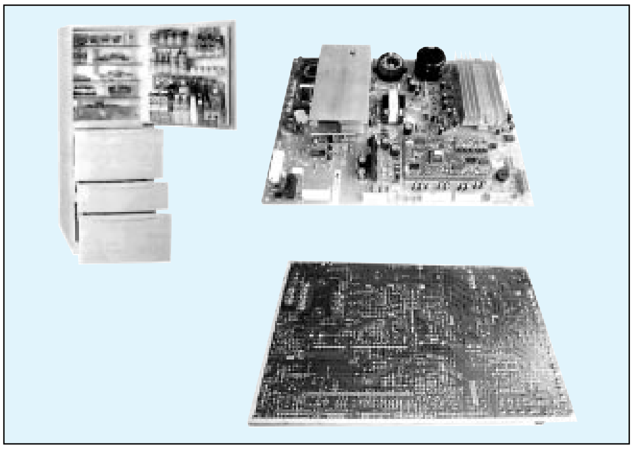

Fig. 4 Hitachi refrigerator PCB
Using lead-free solder (from Hitachi, Ltd.)

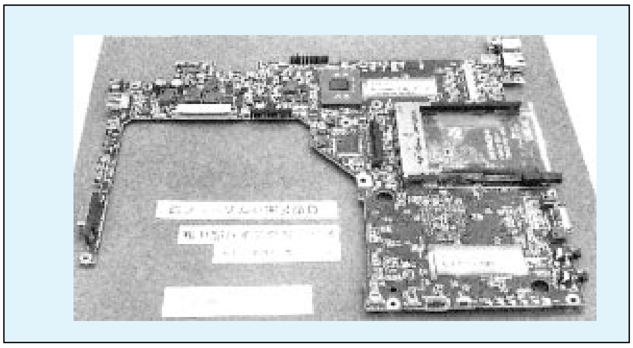

Fig. 5 Hitachi note PC PCB
Using lead-free solder and also halogen-free
(from Hitachi, Ltd.)

Sony completed its adoption of lead-free solder in camcorders in March 2000, and has now begun the changeover in overseas TV manufacturing as well. The solder used at first was Sn-Ag-Bi-Cu and now Sn-Ag-Cu is used. Fig. 6 shows one of these Sony PCBs.

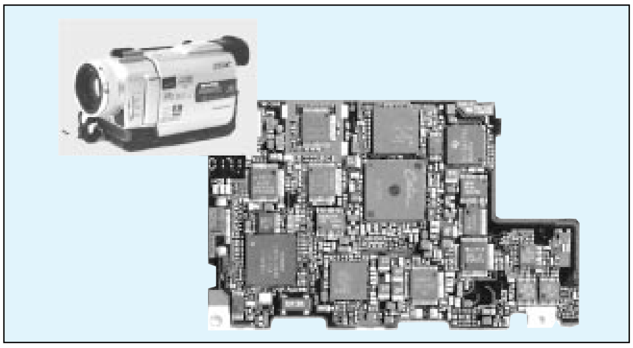

Fig. 6 Sony camcorder and its PCB
Using Sn-Ag-Bi-Cu reflow soldering
(from Sony Corporation)

Toshiba Corporation had already begun manufacturing a large number of lead-free products by the end of the year 2000.

During the year 2000, use of lead-free solder mountings on automobiles was begun. Because automotive design places its highest priority on safety, an exception was made for automobiles in the EU's ELV directive enacted in 2000. However, there are an enormous number of automobiles discarded annually, similar to the situation of home appliances, and so harmful elements such as lead need to be replaced as soon as possible, and each company has plans for eliminating such substances.

Nissan Motor Co., Ltd. has led the field in combating this situation by introducing an Sn-Ag-Cu lead-free solder mounting for its mass-produced keyless entry system PCB, adopted from the summer of 2000. This is probably a global first public proclamation of adopting lead-free solder for automotive use. The PCB for that system is shown in Fig. 7. In America, too, Ford automobiles have lead-free solder mountings on safety lock systems installed from the end of 2000.

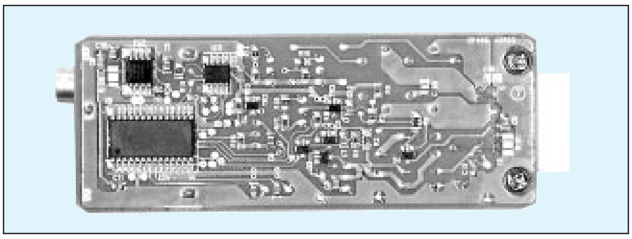

Fig. 7 Rear surface of the lead-free PCB for the Nissan keyless entry system
(from Nissan Motor Co., Ltd.)

In the ways noted above, Japan leads the world in adopting lead-free solder for mass production. The EU announced in June 2000 that planned inauguration of the drafted directive would be delayed for 4 years before the regulation would be enforced. There was some apprehension that companies would not continue moving forward on the issue, but all trends seen since have indicated no slowing of the transition to lead-free solder. Rather, there seems to be even greater haste to make progress. The awareness of the Japanese companies is also shared by American and European companies, and information from the major electronics manufacturers indicates that all are going full speed ahead in promoting lead-free solder mounting.

6. Lead-free solder materials

In the past, Sn-Pb eutectic solder is not the only solder that has been used, a variety of solder compositions have been employed, and even with lead-free solder we must be sure to use the proper material in the proper place. In particular, Sn-Pb solder has been used to cover a wide temperature range, but the need has arisen to substitute the Sn-Pb family of solder for various other alloy compositions. Table 5 presents a summary of the composition and characteristics of current lead-free solders that can be cited, along with notes about their usage. Among the various candidates, the Sn-Ag-Cu family of solder is the strongest candidate to become the next-generation solder. Research in Japan, Europe, and the US indicate this alloy is extremely stable, and accordingly is considered able to meet globally acknowledged standards. However, the compositions being recommended in Japan, Europe, and the US have slight differences. Table 6 shows these differences. Information obtained through simulations and high-precision scientific trials seem to call for a eutectic composition of around Sn-3.5Ag-0.7Cu.

Table 6 Sn-Ag-Cu solder compositions promoted by different countries

Region		Composition promoted
EU	IDEALS Project	Reflow soldering: Sn-3.8Ag-0.7Cu
	Soldertec (ITRI)	Reflow soldering, wave soldering, hand soldered: Sn+(3.4-4.1)Ag+(0.45-0.9)Cu
US NEMI Project		Reflow soldering: Sn-3.9Ag-0.6Cu
Japanese companies of former JEIDA		Reflow soldering, wave soldering: Sn-3.0Ag-0.5Cu

One obstacle for the Sn-Ag-Cu alloy is that raising the melting point creates a corresponding rise in mounting temperature. Sn-Pb eutectic solder has a melting point of 183°C, and a reflow soldering temperature of 230°C is quite sufficient for manufacturing. However, the Sn-Ag-Cu eutectic alloy has a melting point of 216°C, which is 33°C higher than conventional solder. As a result, a reflow soldering temperature of 230°C leaves too narrow a margin and results in almost complete lack of success, and so raising the reflow soldering temperature becomes unavoidable. Higher reflow soldering temperatures

Table 5 Lead-free solder candidate alloy and cautions (units by wt%)

Process		Alloy type	Cautions
Wave soldering		Sn-Ag family: Sn-3.5Ag, Sn-3Ag-0.5Cu Sn-Cu family: Sn-0.7Cu The above alloys with trace amounts of additive elements (e.g., Ag, Au, Ni, Ge, In)	Watch out for PCB damage such as land-lifting and lift-off when used with Sn-Pb parts plating. When using single-side wave soldering, Bi can be added. (However, watch for compatibility problems with Alloy 42 [Invar Alloy].)
Reflow soldering	High-temperature	Sn-Ag family: Sn-3.5Ag, Sn-3Ag-0.5Cu, Sn-(2 to 4)Ag-(1 to 6)Bi The above alloys with 1 to 3% of In as an additive.	Watch out for higher melting points along with reflow soldering temperature control. Care must be taken for compatibility with Bi and Sn-Pb plating.
	Mid-temperature	Sn-Zn family: Sn-9Xn, Sn-8Zn-3Bi	Be careful when applying to special corrosive environments. In particular, the presence of Cl is cause for concern. With copper electrodes, a barrier plating such as Ni or Au should be used to maintain thermal resistance.
	Low-temperature	Sn-Bi family: Sn-57Bi-1Ag	Care must be taken concerning compatibility with Sn-Pb plated parts.
Hand soldering and robot soldering		Sn-Ag family: Sn-3Ag-0.5Cu Sn-Cu family Sn-Bi family	Ensure compatibility before using to repair solder with a different composition.

demand better thermal resistance for semiconductors as well as other parts and PCBs. Concern for this very problem led the US NEMI Project to require 260°C thermal resistance for the industry. In addition to necessitating higher thermal resistance of parts, this approach also necessitates higher precision in mounting temperature control. Urgent development of mounting parts is under way in an effort to limit thermal distribution on PCBs to a minimum, and thus make it possible to handle items such as large PCBs as well as permit the coexistence of large and small parts. Devices with small reflow soldering thermal distribution are already being marketed, and optimized design and parts layout should make reflow soldering temperatures of 240°C feasible even for large PCBs.

The addition of Bi to the Sn-Ag solder family lowers the melting point and improves wettability, making this a very attractive option. On the other hand, a severe defect called lift-off forms when using the Bi additive with wave soldering for double-side PCBs, urgently necessitating suppression countermeasures as well as the ability to ascertain conditions causing the defect. For relevant details, please refer to the separate article.6) It is known that adding more than a certain percentage of Bi results in a weakened interface with Alloy 42 (Invar Alloy: an alloy of nickel and iron used for items such as IC lead frames). This interface already has a low initial strength, which is compounded by striking degradation resulting from thermal fatigue. The cause of this low interface strength has not yet been worked out, and awaits further research. Adding Bi to solder is known to cause compatibility problems with Sn-Pb plated parts. Compatibility difficulties stem from a low melting point phase forming in the interface with Sn-Bi-Pb, and this phase then generates a melting reaction at less than 100°C. Therefore, care must be taken when using Bi additives in solder used with plating containing Pb.

The Sn-Bi family of solder alloys have a eutectic point of 139°C, and are attractive as solder because they can be used for mounting at temperatures below 200°C. Past lack of ductility has been an obstacle, but it has been possible to improve ductility through the use of such additives as Ag. Use of this alloy has made it possible, for example, to adopt Sn-Ag solder as a high-temperature solder making feasible hierarchical junctions (high- mid- and low-temperature multi-stage connections) in mounting. Rather than requiring thermal resistance to exceed 100°C for most home appliance products, a better option would probably be to have this low melting point solder available for a wide range of products. Compatibility problems with Sn-Pb plating are an important concern, just as with Sn-Bi eutectic solder.

The Sn-Zn-Bi family of solder has a melting point of 189°C, making it an alloy with characteristics for mounting that are extremely close to the current Sn-Pb eutectic solder. However, the marked oxidation of Zn yields poor mounting characteristics, and so early on the US and Europe gave up on adopting this type of solder. Japanese manufacturers, however, improved the flux, making it possible to use this solder for mounting with no inferiority at all to conventional technology in the atmosphere. In the future, the possibility exists for developing solder with higher reliability through such means as evaluating resistance to corrosion. Problems of compatibility with Sn-Pb plating are the same as with other solders containing Bi. Currently, this solder contains a 3% Bi additive, but the optimum composition needs to be reconsidered due to severe compatibility problems with Sn-Pb plating and the occurrence of phenomena such as lift-off. The amount of Bi should probably be reduced to less than 3 percent.

The reasonable price of the Sn-Cu family of solder make it an essential alloy for wave soldering applications. However, there is some apprehension about the low reliability of Sn-Cu due to such problems as thermal fatigue, making this a less desirable choice for mountings that demand high reliability. Inferior wettability also make it difficult to properly wet through holes, so this solder will probably need to be limited to such uses as wave soldering on single-side PCBs. Ongoing trials for reliability improvement techniques consist of subtle changes in composition such as adding a third element such as Ag, Au, or Ni. The higher melting point of this alloy at 227°C will not cause major changes in wave soldering temperature conditions compared to conventional Sn-Pb eutectic solder. However, due to concerns about PCB thermal resistance as well as compatibility problems with Pb plated parts, further improvements are needed.

Plating technology for electronic parts has shown exceptional progress during the same time period as the NEDO Project activities. Conventional Sn-Pb plating has poor compatibility with solder containing Bi, and also causes lift-off, making the transition to lead-free plating desirable in the earliest possible time frame. At present, chip parts are almost uniformly plated with Sn, but with lead parts we must adopt the use of various types of solder for various purposes, using solder such as Sn-Ag (the main alternative for chip plating), Sn-Cu, and Sn-Bi. The Sn-Cu plating requires caution concerning whisker generation on some types of PCBs.

Recently, concern has arisen that embrittlement during the α to β metamorphosis in solder such as the Sn-Cu family can lead to tin pest problems. This phenomenon has been recognized for a long time, and suppression countermeasures are also well known.7) Phase metamorphosis research from a scientific point of view is ongoing, and the industry urgently requires clarification of issues such as the effects of super-cooling that impede the metamorphosis naturally expected to occur at 13°C, and also the fundamental effects of suppressing elements and accelerating elements such as Al need further research.

7. Conclusion

As this paper has discussed, lead-free solder mounting has seen the beginning of genuine major development toward practical application over the course of 1 or 2 years. The WEEE/RoHS regulation of solder initially scheduled for 2004 has been postponed until 2006. On one hand, it is possible to claim that this has given us time to spare, but this has had almost no effect on the press for transition to lead-free solder by major manufacturers, either foreign or domestic. Rather, the poor compatibility between lead-free solder and lead-containing solder and lead-containing plating has made it imperative to reduce the time these coexist to the shortest period possible. Therefore, when reliability has been assured, we should not hesitate to immediately make the transition to practical application.

The list below shows the main problems remaining to be solved for lead-free solder. Among them, we could list the fact that even eutectic solder has not yet been fully investigated, but in this unexplored region as well, trends have appeared bringing solutions that accompany development efforts for lead-free solder.

Unsolved technical problems for lead-free solder

1. Clarification of the lift-off phenomenon and establishment of suppression measures
2. Establishment of lead-free plating technology and whisker countermeasures
3. Lower soldering temperatures and process optimization
4. High-temperature solder
5. Low-temperature embrittlement (tin pest)
6. Construction of a database of physical properties (solder, parts, PCBs)
7. Establishment of reliability design technology
8. Standardization of solder materials evaluation technology

Sn-Pb solder has been easy and convenient to use, and has been seen as the “grand champion of solders.” However, this is not an accurate portrayal. The use of Sn-Pb solder has caused a number of failures and accidents. On the other hand, lead-free solder, represented by Sn-Ag-Cu, can certainly show improved reliability under suitably selected application conditions for mounting.

Sn-Ag eutectic solder has clearly shown high reliability in its use to date. Therefore, if we return to the starting point of lead-free solder mounting, we can immediately stop the continued release of lead into the environment and we can accumulate technological know-how. We must establish highly reliable lead-free solder mounting technology at the earliest possible moment.

At this point, I would like to briefly mention the patent problems surrounding Sn-Ag-Cu. The Sn-Ag-Cu alloy is recognized around the world as leading the list of candidates for use as lead-free solder. The University of Iowa in the US and Senju Metal Industry Co., Ltd. in Japan hold separate patents with minute differences on the range of composition of this alloy. The range of the US patent application is still in dispute, but to attain an environment in which consumers around the world can use equivalent products with peace of mind, we must have both parties working in unison at the earliest possible time. Through the efforts of the parties involved, a comprehensive agreement on both patents has gradually been achieved within Japan. Based on this agreement, we have been able to safely export to the US products using Sn-Ag-Cu manufactured only in the Japanese domestic market. Currently, it seems that this agreement will be extended to cover products manufactured abroad, and we fervently hope that an agreement will be concluded without delay.

The standard solder of the future will not specifically be only Sn-Ag-Cu, but we must also ascertain the possibilities and range of suitability for such solder types as Sn-Zn, Sn-Bi, and Sn-Cu. To select correctly from among the possibilities which alloys and processes will become the final standards, we need to immediately construct a database, and in order to realize such objectives, we need to organize strong cooperation among industry, government, and academia.

Conductive adhesives hold out high hopes as one possibility for the adoption of lead-free solder. This very interesting technology contains possibilities for expansion in such areas as super thermal resistance, elimination of flux, and use with fine pitch applications. This subject is beyond the scope of this article, but it bears discussion in a separate article if the occasion presents itself. Other topics that I have not been able to cover within the realm of this article, such as technological trends and environmental information concerning lead-free solder, are covered in my work listed below, and I would be very pleased if you find that helpful.

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