# Assembly Technology Using Lead-free Solder

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**In the process of complying with the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS) Directive enforced on July 1, 2006, the major technical issue to be addressed regarding the six substances restricted by RoHS is replacing lead, which is used a variety of ways in said equipment. The replacement of lead, especially with regard to solder (the so-called basic material of electronic assembly), requires controlling the heat resistance of electronic components. Moreover, a means must be devised to maintain uniform temperature for each material and component at reflow soldering since commonly used tin-silver-copper (Sn-Ag-Cu) solder, if adopted, requires a higher soldering temperature than lead containing solder. Additionally, it is important to clarify the properties, quality, and reliability of any new, alternative solder materials. Fujitsu has been engaged in comprehensive engineering, such as developing basic lead-free solder materials, to apply lead-free solder to its products. This paper introduces Fujitsu's activities toward addressing the technical issues posed by lead-free soldering technology.**

## 1. Introduction

The Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS) Directive implemented on July 1, 2006, now restricts the use of six substances — lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium ($Cr^{6+}$), brominated flame retardants polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDE) — in several countries around the world due to growing environmental concerns. Electronics manufacturers are consequently scrambling to cope with these new restrictions.

Of the six substances restricted by the RoHS Directive, lead is the most widely used, as it is the basic material utilized in electronic soldering. Replacing lead is therefore a top-priority issue for the electronics manufacturing sector.

To address this issue, Fujitsu has proceeded with the development of lead-free soldering materials and lead-free soldering technology.

This paper outlines Fujitsu's efforts to solve the problems of lead-free manufacturing.

## 2. Issues of lead-free manufacturing

The practical use of lead-free solder has been researched in many fields. Currently, the tin-silver-copper (Sn-Ag-Cu) solder alloy is the primary substitute for conventional tin-lead (Sn-Pb) solder material. While Sn-Ag-Cu solder is reliable, its melting point is 35°C higher than that of Sn-Pb solder. Since Sn-Pb eutectic solder is now used for jointing existing electronic components, the higher temperature required for Sn-Ag-Cu reflow soldering poses the risk of damaging electronic components.note)

In addition, it is important to assess the quality and reliability of any new, lead-free solder material used to replace conventional soldering material. It also is necessary to check the suitability of a given lead-free solder for jointing and mounting various components, as well as its suitability for the terminal surface finishing of electronic components.

Therefore, lead-free soldering entails the following:

1) Measures must be taken to guard against potential damage to components caused by higher soldering temperatures.
2) The quality and reliability of lead-free solder joints and materials, and their suitability for a given application must be verified.

We will now focus on dealing with these two issues.

## 3. Measures for dealing with rise in soldering temperatures

All electronic components have a certain resistance to the higher temperature that results from reflow soldering with Sn-Ag-Cu solder. The heat resistance of electronic components is described below, followed by the heat-resistance requirements, standards, and reflow temperature homogenization developed by Fujitsu.

### 3.1 Rise in reflow soldering temperature range

The temperature range ($\Delta T$) between the temperature required for creating joints with reflow soldering and the temperature limits of electronic components are usually determined as illustrated in the diagram shown in **Figure 1**.

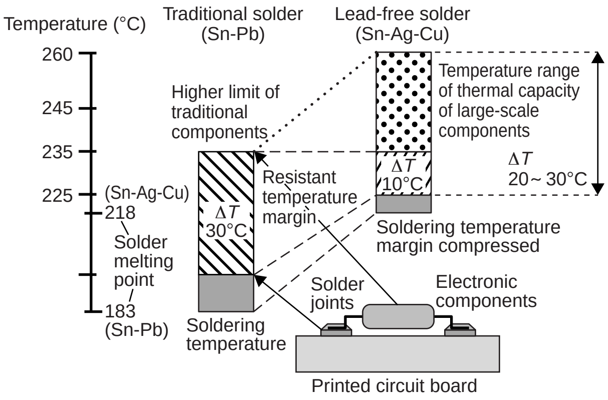

Figure 1
Rise in reflow soldering temperature.

In cases where Sn-Pb eutectic solder is used, the temperature required for reflow soldering can be kept lower, so that $\Delta T$ is approximately 30°C. In other words, there is an approximate 30°C difference between the temperature required for the joint and the temperature at which electronic components may be damaged. Conversely, the use of Sn-Ag-Cu solder entails a higher soldering temperature, so that the components are soldered in $\Delta T$ of approximately 10°C. However, current printed circuit boards typically require $\Delta T$ of 10°C to 20°C. Furthermore, when dealing with the large-scale printed circuit boards used in large servers, and with boards loaded with components of varying thermal capacities, there may be cases requiring $\Delta T$of 20°C to 30°C. Therefore, any components used with lead-free soldering must be resistant to high temperatures.

### 3.2 Heat-resistance requirements for electronic components

In 2001, Fujitsu presented the heat-resistance requirements indicated in **Figure 2** to its component manufacturers and requested their cooperation in line with Fujitsu's efforts to become a lead-free manufacturer. Fujitsu has introduced three levels of heat-resistance rankings. First, 260°C is the basic heat-resistance requirement, while resistance ratings of 245°C and 235°C are used to classify existing electronic components.

These heat-resistance requirements were

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note) This refers to the soldering temperature of the reflow method, where electronic components are mounted after solder (paste) is printed, and then immediately heated in an oven (reflow furnace).

| Heat resistance (°C) | Preheat time 160 to 180°C t2 (s) | Main heating | | | | Times of Reflow |
|---|---|---|---|---|---|---|
| | | Temperature (°C) | | Time (s) | | |
| | | T4 | Tmax. | t3 | t4 | |
| 260 | ≥ 160 | 255 | ≥ 260 | ≥ 80 | ≥ 10 | 2 |
| 245 | ≥ 120 | 245 | ≥ 245 | ≥ 70 | ≥ 10 | |
| 235 | ≥ 120 | 235 | ≥ 235 | ≥ 60 | ≥ 10 | |

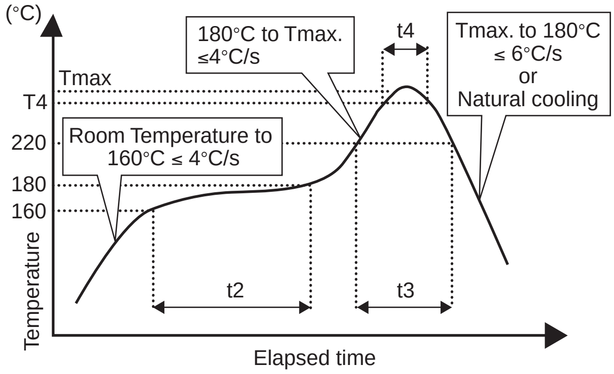


Figure 2
Heat-resistance requirements and standards developed by Fujitsu for electronic components.

developed as standards for enabling Sn-Ag-Cu soldering after examining the reflow soldering temperature requirements at Fujitsu's manufacturing facilities. Between 2002 and 2004, the Joint Electron Device Engineering Council (JEDEC), the organization that standardizes semiconductor parts, also revised their heat-resistance standards for lead-free manufacturing to include three temperature levels, including 260°C.1)

While electronic component makers are now manufacturing products in accordance with RoHS regulations, the enhancement of heat resistance is linked to such basics as component structure and construction materials. Still, such technical issues as the moisture absorbent of resin materials must be solved. While the heat resistance around chip components is almost adequate, the relatively older components in quad flat packages (QFP) and ball grid array (BGA) packages often lack enhanced heat resistance. Moreover, some aluminum electrolytic capacitors cannot withstand high temperatures over the time required for reflow heating, since such temperatures exceed the boiling point (approximately 200°C) of electrolytic solution contained within the capacitor.

## 3.3 Equalization of reflow temperature

There are various types of electronic components mounted on printed circuit boards, and each has a different thermal capacity. As shown in **Figure 3**, components heated in a reflow furnace exhibit differences in temperature as a result of these differing thermal capacities. Due to the high temperature required for reflow soldering with Sn-Ag-Cu solder, the temperature dispersion of components across a printed circuit board could become quite large. To counter this situation, manufacturers have introduced high-performance reflow furnaces that equalize the dispersion of heat across a circuit board.

## 3.4 Reflow simulator

In an effort to equalize reflow temperature distribution, Fujitsu has developed and commercialized software that simulates reflow heat transmission.2) This allows a reduction in $\Delta T$ at the design stage by making it possible to position each component on a circuit board so as to even out heat dispersion.

Using this reflow simulator allows the temperature distribution of electronic components positioned on a printed circuit board to be viewed quite clearly. This is very useful, given the difficulty of simultaneously measuring the temperature of components mounted on a physical printed circuit board, due to restrictions on thermocouple installation. The reflow simulator enables the temperature of all modeled components and joints to be examined simultaneously, thus making it possible to confirm the manufacturability of a given circuit board before it is created. **Figure 4** shows an example of simulated reflow temperature distribution on a printed circuit board.

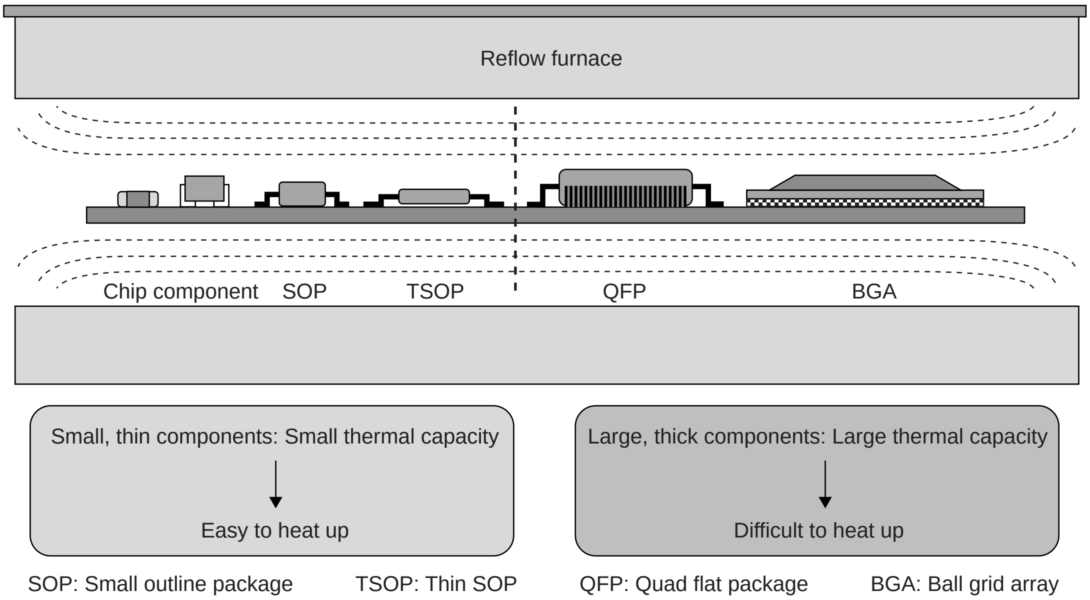


Figure 3
Temperature of electronic components during reflow soldering.

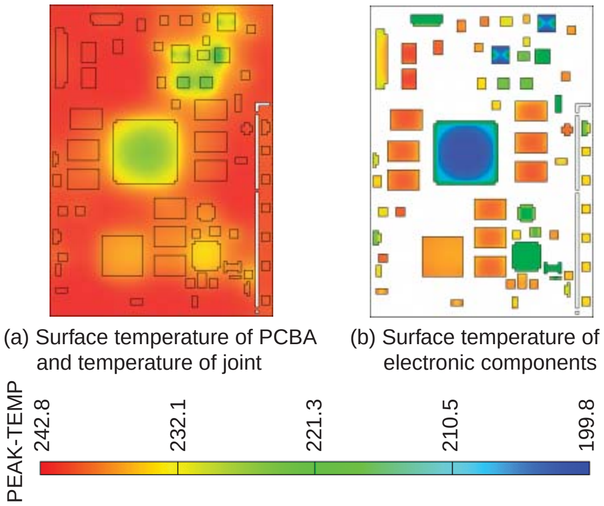


Figure 4
Simulation result of temperature distribution on printed circuit board assembly (PCBA).

## 4. Verifying the quality and reliability of lead-free solder

For some manufacturers, the problem posed by the heat resistance of electronic components has hindered the implementation of Sn-Ag-Cu solder. In order to address this problem, Fujitsu researchers have developed lead-free solder materials with melting points lower than that of Sn-Ag-Cu solder. This section describes the characteristics, quality, and reliability of lead-free solder as compared to conventional Sn-Pb eutectic solder.

### 4.1 Comparisons of lead-free solder properties

Fujitsu has developed the following three types of lead-free solder: high-temperature Sn-Ag-Cu solder, medium-temperature Sn-Zn-Al solder, in which a small amount of aluminum (Al) is added to a tin-zinc (Sn-Zn) solder alloy, and low-temperature Sn-Bi-Ag solder, in which silver (Ag) is added to a tin-bismuth (Sn-Bi) alloy. **Table 1** compares the basic properties of these lead-free solders with conventional solder (Sn-Pb).

Although provided as a reference for assembly design, these property measurements should be used carefully given the possible variance depending on the method of testing the materials and the measurement conditions. When comparing the mechanical properties of each solder, the lead-free solders show a higher Young's Modulus (modulus of longitudinal elasticity), less elongation, and tend to become firm when compared to

Table 1
Comparison of basic properties of each solder.

| Solder<br>Property | Sn-Pb | Sn-Ag-Cu | Sn-Zn-Al | Sn-Bi-Ag | Unit |
|---|---|---|---|---|---|
| Melting point | 183 | 218 | 199 | 138 | °C |
| Density | 8.5 | 7.4 | 7.3 | 8.6 | g/$cm^3$ |
| Coefficient of thermal expansion | 24 | 21 | 24 | 15 | $10^{-6}$/°C |
| Specific heat | 197 | 234 | 243 | 170 | J/(kg·K) |
| Thermal conductivity | 50 | 55 | 66 | 21 | W/(m·K) |
| Thermal diffusivity | 30 | 31 | 37 | 14 | $mm^2$/s |
| Surface tension | 420 | 450 to 500 | 518 | 380 to 390 | mN/m |
| Young's modulus | 22 | 31 | 36 | 24 | GPa |
| Poisson's ratio | 0.37 | 0.4 | 0.44 | 0.43 | |
| Tensile strength | 41 | 35 | 46 | 60 | MPa |
| Shearing strength | 27 | 30 | 32 | 36 | MPa |
| Yield stress | 28 | 27 | 27 | 35 | MPa |
| Elongation | 38 | 23 | 25 | 40 | % |
| Vickers hardness | 13 | 15 | 19 | 15 | Hv |
| Electrical resistivity | 15 | 11 | 12 | 34~58 | μΩ·cm |

conventional Sn-Pb eutectic solder. Although lead-free solder tends to have a higher material strength, the possibility of greater stress on the components and printed circuit boards should be kept in mind.

Regarding the fatigue characteristics of solder, the distortion resistance has been repeatedly verified by such tests as the dynamic measurement of viscoelasticity that results from torsion fatigue testing.3) Generally, the fatigue characteristics of lead-free solder alloy such as Sn-Ag-Cu tend to be superior to those of Sn-Pb eutectic solder.

### 4.2 Verifying the quality/reliability of solder when used on components

Manufacturers have already begun the lead-free production of electronic component terminal materials. Although various types of plating are used for such component terminals, it is important to check the wettability and compatibility of joint strength during the jointing solder process. When Fujitsu initiated efforts to become a lead-free manufacturer, it worked with a Japanese plating agent manufacturer to evaluate solder joints against terminal plating. For this evaluation, a QFP lead component sample that satisfied the process requirements for each type of lead-free plating was prepared.

For the Sn-base plating, the proportion of additive elements is adjusted for pure Sn plating and such alloy plating as Sn-Ag, Sn-Bi, and Sn-Cu. Then, a basic evaluation of the changed Ag, Bi, and Cu (in the range of 0 to 5%) is conducted to verify the reliability of solder wettability and the joint strength.

Moreover, "tin whiskers" (whisker-like crystals that grow on the plate surface) are checked and assessed for the Sn-base plating.

### 4.3 Structural analysis simulation

Since the stress level of a solder joint can be predicted through structural analysis simulation, the reliability of the solder joints of each component mounted on a printed circuit board is verified using an assembly evaluation experiment. In structural analysis simulation, the stress distortion and creep properties of the solder alloy are used as nonlinear properties. Such structural analysis simulation is often used for BGA and chip scale package (CSP) components. **Figure 5**[4) ] shows an example of joint fatigue life evaluation using thin small outline package type-I (TSOP-I) components. Such components, however, have a low level of structural stress relief among lead terminal type components.

In TSOP-I, the difference in thermal expansion between components and the printed circuit board caused by a rise in temperature is large, thus facilitating a significant expansion and contraction (thermal strain). The stress of TSOP-I may be predicted to be greater than that of low-profile quad flat package (LQFP) and TSOP type-II (TSOP-II) components. As shown in Figure 5 (a), the relatively short height of the lead terminal, and the lead terminal drawn from the lengthwise position of the component package cause this stress.

This evaluation example illustrates how fatigue life is calculated. The lead terminal material of the component, the quantity of joint solder, and the solder material are used as parameters in simulating the thermal strain obtained from the temperature cycle test. As indicated in Figure 5 (b), this analysis clearly shows that the fatigue life of Sn-Ag-Cu solder is superior. Among lead terminal materials, Cu is softer than iron-nickel (Fe-Ni) alloy (42Alloy) and has a longer life. This also shows that the fatigue life varies depending on the quantity of solder, and that the relation between the quantity of solder and fatigue life differs, depending on the solder material.

## 4.4 Characteristics of each solder and applied products

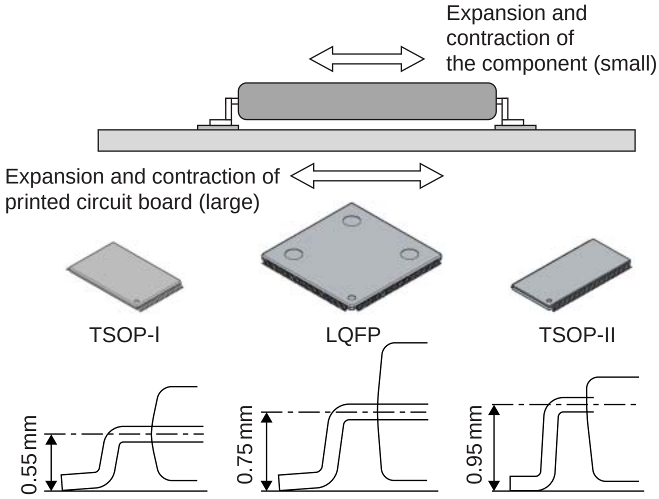
The following describes the characteristics of high-temperature Sn-Ag-Cu solder, medium-temperature Sn-Zn-Al solder, low-temperature Sn-Bi-Ag solder, and the products to which each solder is applied.

1) High-temperature Sn-Ag-Cu solder

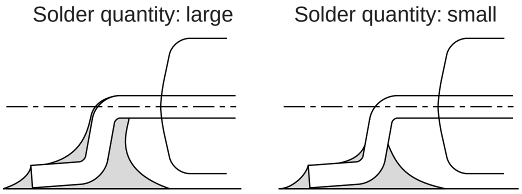
Sn-Ag-Cu solder is more reliable on joints than Sn-Pb eutectic solder. Therefore, it is used in the majority of lead-free products manufactured by the Fujitsu Group.

2) Medium-temperature Sn-Zn-Al solder

Sn-Zn-Al solder has a melting point near that of conventional Sn-Pb eutectic solder. It offers great potential as it requires no precious metals and is therefore inexpensive. Since the supplementation of Al results in earlier surface oxidation



(a) Comparison of lead terminal type components.



| Material of Lead terminal | Solder quantity | Fatigue life (cycle) | |
|---|---|---|---|
| | | Sn-Pb | Sn-Ag-Cu |
| 42 Alloy | Large | 959 | 1844 |
| | Small | 922 | 2663 |
| Cu | Large | 1066 | 2707 |
| | Small | 3536 | 3856 |

(b) Fatigue life per condition of TSOP-I

Figure 5
Joint fatigue life evaluation of TSOP-I.

of Al than of Zn, this solder effectively curtails the degradation of solder wettability caused by Zn oxidation.5) The application of Sn-Zn-Al solder has been expanded from LCD products, and more than one million products have been manufactured using Sn-Zn-Al solder.

3) Low-temperature Sn-Bi-Ag solder

Sn-Bi-Ag solder is applied to Fujitsu's mainframe products. This solder alloy enables manufacturers to create joints with a low-temperature process that reduces distortion during assembly, and allows the implementation of large components, as well as multiple temperature ranks, which provide an easy way to replace and rework sub-module assemblies, when used with an Sn-Ag-related alloy. The supplementation of Ag improves the elongation of the Sn-Bi alloy, which is harder than conventional solder (Sn-Pb), thus achieving higher joint reliability when encountering heat stress, shock, and vibration.6)

## 5. Technical developments for coping with high-temperature lead-free solder

Although Fujitsu has made impressive breakthroughs in its development of lead-free solder as described above, processes using Sn-Ag-Cu solder still require higher temperatures than those needed for conventional soldering. As such, Fujitsu needed to deal with such issues as the release of heat stress during such processes as component replacement and reworking, and dissolution of the printed circuit board Cu conductor. This section describes the technologies employed for the measures developed to address these problems.

### 5.1 Measures for replacing and reworking BGA components

Generally, a local heating method using hot air is used for replacing BGA components. This method differs from the bulk heat generated in the reflow furnace and requires a reduction of heat in the area around the circuit board, a condition that is difficult to control. In order to restrain heat stress, Fujitsu developed a method of reducing the rise in temperature in other components (that are not to be reworked) and on the surface of the printed circuit board. **Figure 6** shows where the components requiring increased thermal capacity are located, and insulation placed around the components that are to be reworked.

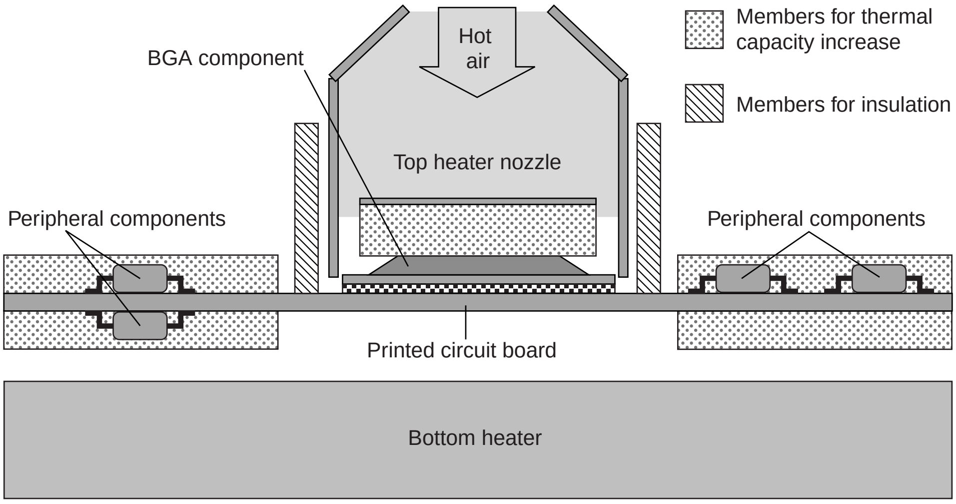


Figure 6
Rework process for replacing BGA components.

### 5.2 Measures to prevent dissolution of the printed circuit board Cu conductor

When inserted components are replaced by using the flow (DIP: Dipping and Pulling) method, in which soldering is done with immersion in molten solder, it takes a long time to heat up the components around the component being replaced. This type of local heating can result in Cu dissolution, during which the printed circuit board conductor simply diffuses into the solder. To prevent Cu dissolution, the Fuji Electric Group developed Sn-Ag-Cu-Ni-Ge solder,7) in which small amounts of nickel (Ni) and germanium (Ge) are added to the Sn-Ag-Cu. As indicated in **Figure 7**, compared to Sn-Ag-Cu solder, Sn-Ag-Cu-Ni-Ge solder slows Cu dissolution more effectively.

## 6. Issues posed by application of medium/low-temperature lead-free solder

Both medium-temperature Sn-Zn-Al solder and low-temperature Sn-Bi-Ag solder enable the use of components and printed circuit boards having low heat resistance. However, both also have unique application issues and weaknesses that must be fully understood before utilizing this technology.

### 6.1 Issues posed by Sn-Zn-Al solder

Sn-Zn-related solders were originally not easy to use, due to the high reactivity of Zn and the narrow temperature and time ranges during reflow preheating. However, the solder paste flux has been improved so as to reduce the reactivity of Zn. As such, manufacturability has been significantly improved.8) A different problem may arise when the terminals of a component are thickly plated with gold (Au). There have been cases where a gold-zinc (Au-Zn) alloy remained in the membrane of the solder. This film of Au-Zn alloy can become the starting point for cracks to form in the solder. After evaluating this problem, the Au plate thickness is now restricted to less than 0.25 μm on components that include Sn-Zn-Al solder applied products. Fujitsu thus pays close attention to the selection of components to which Sn-Zn-Al solder is applied.

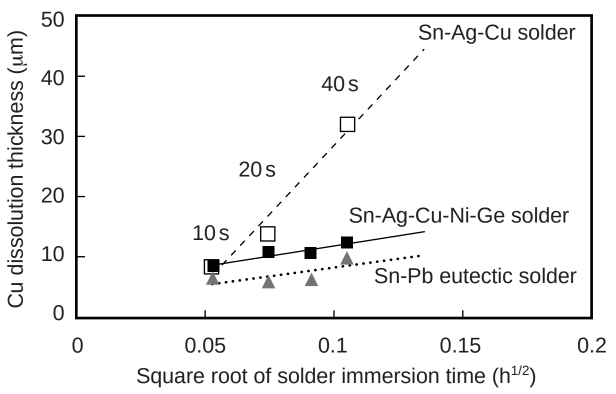


Figure 7
Comparison of Cu dissolution speed of solders.

### 6.2 Issues posed by Sn-Bi-Ag solder

When lead (Pb) is included in the terminals of a component to which Sn-Bi-Ag solder is applied, the Sn-Pb-Bi phase generates a low melting point of around 96°C. As a result, it is essential that terminals of the component be lead-free. Moreover, the U.S. Electronic Industries Alliance (EIA) and the Japan Green Procurement Survey Standardization Initiative (JGPSSI) have prepared the Joint Industry Guide for Material Composition Declaration for Electronic Products (JIG) that designates Bi as a “Level B” substance. While Bi is not a restricted substance, its recycling and use are monitored as a Level B substance.

There are ongoing studies on the practical use of medium/low-temperature lead-free solder through a collaboration between industry, academia, and the government, and through research and development being conducted under the auspices of Japan’s Ministry of Economy, Trade and Industry (METI). Until March 2007, these studies will continue under the theme of “The establishment and standardization of fundamental technology for low-temperature, lead-free solder assembly”.9) Given these extensive resources dedicated to research and development, breakthroughs in the expansion of medium/low-temperature solder applications can be expected.

## 7. Conclusion

This paper reviewed Fujitsu's past efforts toward becoming a leader in lead-free soldering technology.

In the future, regulations on environmental protection designed to encourage recycling and counter global warming will be expanded. Given the ongoing research on the environmental impact of various substances and the need for recycling efficiency, more substances may become restricted or regulated, above and beyond those identified by the RoHS Directive.

In addition, future electronics packaging technology is expected to become more environmentally friendly, thus making it easier to safely recycle and reuse older components. With this mind, Fujitsu believes that lead-free soldering technologies, which are more reliable and reusable than conventional methods, should be further developed.

Fujitsu is now proactively promoting and pursuing the development of these technologies in the interest of global environmental protection, and will continue to do so in the future.

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