WP372 (v1.2) October 27, 2014

Lead-Free Solder Ball Characteristics

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Government regulations on the use of certain hazardous materials in electronics have become more stringent. On July 1, 2006, the European Union (EU) issued the Restriction of Hazardous Substances Directive (RoHS), which contained regulations pertaining to the presence of hazardous materials in electrical and electronic equipment. At this writing, non-EU countries (including China, Japan, and others) have adopted or are in the process of adopting equivalent or similar regulations.

One of the intents embodied in these regulations is the near-elimination of elemental lead (Pb), used in the fabrication of BGA package solder balls. To comply with these regulations, BGA package solder balls (commonly made of eutectic solder, $Sn_{63}Pb_{37}$) had to be re-engineered to use only Pb-free solders (SnAgCu or SnAg).

Xilinx maintains compliance with RoHS solder guidelines by providing SnAgCu (known as SAC) solder balls on all FFG-designated device packages.

Industry Status of Pb-Free Solder Applications

Since the introduction of the Pb-free initiatives, both industry and academia have extensively investigated solder ball composition and proposed the use of SAC305/405 solder alloys because of their high strength and reasonable melting points. Xilinx is following industry practice in using SAC305/405 solders in its Pb-free products.

Now that Pb-free device packages are in high-volume production, the industry is discovering that these alloys are more likely than eutectic solder to produce high ppm levels of inter-metallic compound (IMC) fractures when under high strain rates. Strain sufficient to cause IMC fracturing can occur during handling, socketing, or shipping.

Modulus Comparison between $Sn_{63}Pb_{37}$ and Pb-Free Solder

Table 1 and Figure 1 show the modulus of $Sn_{63}Pb_{37}$, SAC305, and SAC405 solders. It can be seen that the Pb-free solders have a higher modulus but less elongation compared to the eutectic $Sn_{63}Pb_{37}$ solder. A higher modulus and less elongation make Pb-free solders somewhat stiff and brittle.

Table 1: **Characteristics of Eutectic ($Sn_{63}Pb_{37}$) and SAC (Pb-Free) Solders**

Alloy	Modulus [GPa]	UTS [MPa]	Elongation [%]
Eutectic: $Sn_{63}Pb_{37}$	40.2	57.3	50
SAC305: $SnAg_3Cu0.5$	51.0	53.3	46
SAC405: $SnAg_4Cu0.5$	53.3	52.4	35

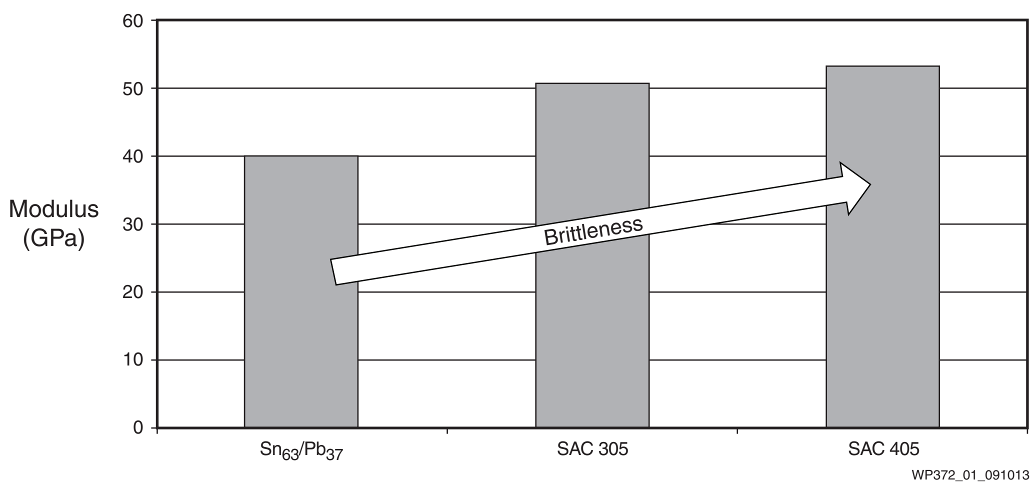

Figure 1: **Modulus Comparison between $Sn_{63}Pb_{37}$ and Pb-Free Solders**

IMC Brittle Fracture under High Strain Rate

Xilinx products use Electrolytic NiAu or Cu solder on pad (Cu SOP) as the BGA pad surface finish.

With a NiAu/SAC solder interface, the IMC layers most typically formed between the BGA pad and solder ball are $(CuNi)_3Sn$ and $(CuNi)_6Sn_5$; with a CuSOP/SAC solder interface, typical IMC layers formed are Cu_3Sn and Cu_6Sn_5. Because the IMC layer is brittle, fractures can occur if the solder joint is subjected to high strain rates (approximately 10^1–10^2/sec, dynamic to impact loading condition), as shown in Figure 2.

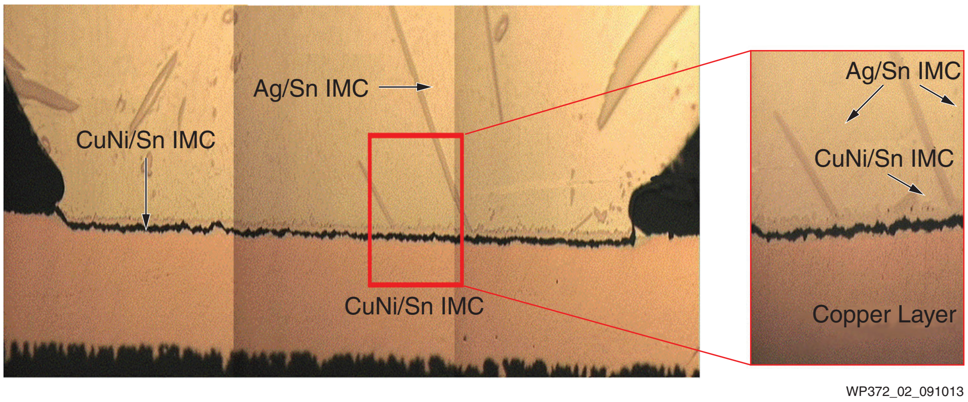

Figure 2: **Typical Pb-Free Solder IMC Fracture under High Strain Rate**

Figure 3 shows a typical industry stress-strain graph for Pb-free solders showing the increase of stress plotted against an increasing level of strain. Note that when even a very high level of strain is applied *quasi-statically* (the "Quasi-Static" curve), Pb-free solders tend to resist high levels of stress that can cause catastrophic failure. This is because quasi-static strain causes the solder ball go into a plastic-like deformation phase that tends to resist creating high levels of stress on the solder interface.

If impact loading is applied, however (the "High Strain Rate" curve), stress increases dramatically to the point where catastrophic failure at the interface can occur. This characterization of stress response to high-impact strain shows that products manufactured using Pb-free solder technology require especially careful handling. Xilinx recommends that a force of not more than 5.0 grams per external solder ball be applied.

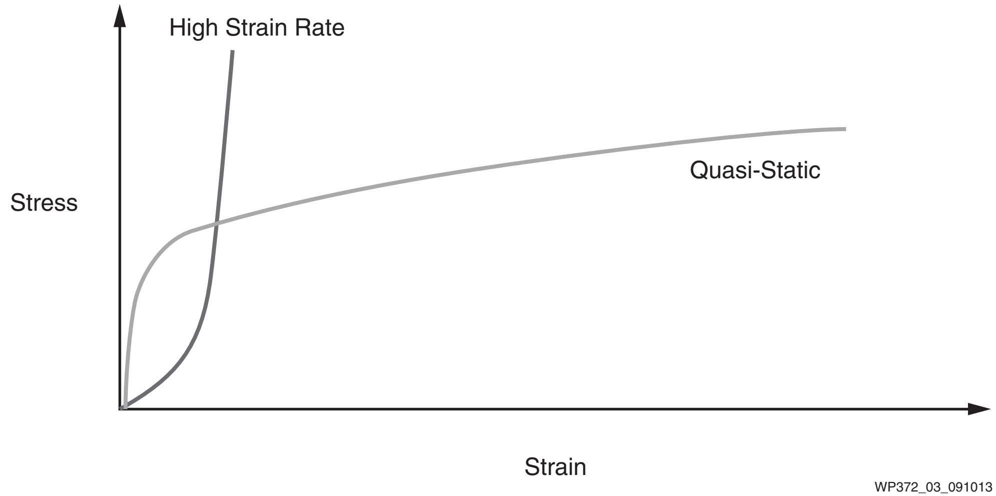

Figure 3: **Pb-Free Solder Response under Different Strain Rates**

Summary and Recommendation

- The industry-wide replacement of eutectic $Sn_{63}Pb_{37}$ solder by Pb-free solders is for environmental and regulatory reasons, *not* for technical improvement. SAC305 and SAC405 are the mainstream formulation choices for Pb-free solder.
- Unlike eutectic solder, Pb-free solders cause a brittle IMC layer to form between the solder ball and the BGA pad. For Xilinx products, this IMC layer is typically composed of $(CuNi)_3Sn$ and $(CuNi)_6Sn_5$, or (depending on the type of solder interface used) Cu_3Sn and Cu_6Sn_5.
- High strain rate loading of Pb-free solder balls can cause the brittle IMC layer to fracture. On the other hand, quasi-static strain loading, though causing plastic deformation of the solder ball, is not seen to be associated with increased IMC fracturing.

It is strongly recommended, therefore, that strain-minimizing controls be put in place wherever Pb-free BGA packages are used, especially during board mounting, testing/handling, and shipping. Avoiding high-rate strain on these devices tends to result in fewer IMC-related failures.

Revision History

The following table shows the revision history for this document:

Date	Version	Description of Revisions
06/28/10	1.0	Initial Xilinx release.
09/10/13	1.1	Changed title, updated abstract, Industry Status of Pb-Free Solder Applications, Modulus Comparison between $Sn_{63}Pb_{37}$ and Pb-Free Solder, IMC Brittle Fracture under High Strain Rate, and Summary and Recommendation.
10/27/14	1.2	Updated Table 1.

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