Impact of pad finish on mechanical shock resistance of lead-free solder joints tested under shear and in pull mode

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Abstract

Fracture of Intermetallic Compounds (IMC) under mechanical shock is a major concern for soldered components. While most shock tests are performed under shear load, a specially designed sample setup is designed and fabricated allowing testing under axial pull direction. These samples are fabricated with two pad finish - NiAu and SAC HASL - and comparing solder mask versus non-solder-mask pad defined solder joints. A mini scale of the Charpy equipment setup measures the energy taken up by the solder joints before fracture. The impact of thermal ageing on the shock resistance is also investigated.

Key words: IMC fracture, HASL and NiAu pad finish, mechanical shock resistance, thermal ageing,

Introduction

Brittle fracturing in solder joints is an increasing problem and the results from several research studies show that lead-free soldering is increasing the risk for brittle fracturing [1]. One reason is the higher elastic modulus and higher yield stress which are typically 50% higher than for SnPb solders. Also higher T_g boards and use of stiffer mould compound packages [2] As a consequence, the stresses induced in and around the solder joints are also typically 50%. Another reason is that thicker and more complex IMC (InterMetallic Compound) layers are formed when lead-free solders are selected.

Brittle fractures are caused by a high level of applied strain and strain rate. This can happen during assembly, in-circuit testing and shipping but also during its product life, e.g. dropping it to the ground. Other causes of high strain rate induced fractures are fast temperature changes and mechanical vibration. However, brittle fractures are sometimes also found during temperature cycling where no mechanical shock stress is induced.

The brittle fracture takes place in the layer of IMC that is formed at the solder/metal interface during soldering. The composition, the geometrical structure and robustness (brittleness) of this IMC layer are determined by the solder composition and the metal finish on the soldered surface (at component and PCB side). There are many different kinds of finishes, the IMC layers are almost exclusively formed to one of the three metal surfaces: copper, electrolytic nickel and electroless nickel. Other finishes plated on top of these (e.g. immersion Sn, immersion Ag, Au flash, etc.) are normally dissolved in the solder. The main trends found in literature are:

- *Copper finishes* (OSP, immersion Ag, immersion Sn, HASL): the IMC formed after soldering is Cu_6Sn_5, and afterwards, a second layer consisting of Cu_3Sn is formed on top of Cu_6Sn_5.
- *Electrolytic Nickel – Electrolytic Gold*: the IMC formed is Ni_3Sn_4. Thanks to the absence of P, it is therefore less prone to brittle fracture. However, the electrolytic Au is much thicker (>300 nm) and this Au dissolves into the solder and forms, after thermal ageing, a second IMC layer of $(Au,Ni)_4Sn$ on top of the Ni_3Sn_4. Also the interface between these two IMC's is weak and prone to brittle fracture. The problem is less severe for lead-free solders thanks to the Cu which forms the $(Cu,Ni)_6Sn_5$ IMC instead Ni_3Sn_4.
- *Electroless Nickel– Immersion Gold* (ENIG): the IMC formed is Ni_3Sn_4. With a too high P

concentration, also the Ni_3P layer is formed at the uppermost Ni surface. The interface between Ni_3P and Ni_3Sn_4 is very weak (“black pad”).

Solder joints formed on Nickel surface have been found to be prone to brittle fractures also in the absence of black pad. It is the scope of this work to measure both qualitatively and quantitatively the resistance to brittle fracture for both copper and nickel surfaces. In this work, only ENIG surfaces are investigated as Nickel finish alternative.

Regarding the testing of shock resistance, many techniques are used and reported in literature [3,4]. Traditional shear and pull tests are not adequate for assessing the risk for brittle fractures. The shear and pull rates used are too low in order to get high enough strain rate. Standards for characterising the fracture strength of solder joints are using bend and drop tests, developed by JEDEC [5] and IPC, but it is difficult to get quantitative numbers out of the tests (package and board dependency).

In order to have a more quantitative number of shock resistance of real size solder joints, an own measurement setup and a specific sample design in performed in this work.

Measurement approach using a miniaturised Charpy tool

The mini-Charpy measurement system, shown in Figure 1, allows us to measure the shock resistance of solder interconnects. It is a miniaturised version of the big Charpy system allowing to do measurements of much lower absorbed energies. The hammer indents the sample with an impact energy which is related to its initial height. If the impact energy is high enough, all solder joints will break and the hammer continues to a lower height than the initial point. The difference in height is the sum of the loss energy due to friction (which should be kept minimal) and the energy absorbed by the sample. In that sense, the system measures the ductility of the tested assembly: ductile materials take up more energy while brittle materials break at minimal absorbed energy. As samples are mounted to a block which can be cooled with liquid nitrogen, samples can be tested at very low temperatures (down to -100°C). In this work, this feature hasn’t been used as all tests were performed at room temperature.

The energy taken up by the sample is given by

$$E_{absorbed} = mgl(-\sin\alpha_2 + \sin\alpha_1) - E_{friction}$$

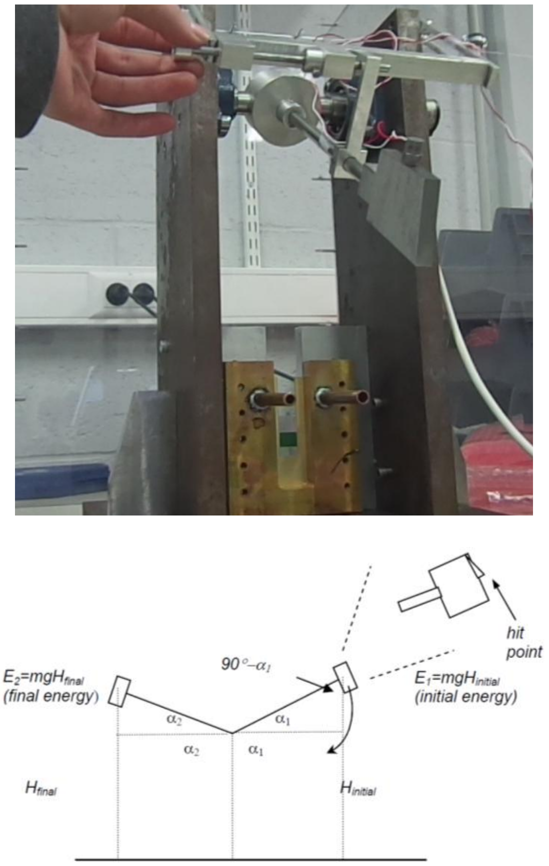

Figure 1: Mini-Charpy measurement system for shock tests on soldered assemblies

Sample description

This mini-Charpy system can be used to apply a horizontal shock on a component soldered to a regular printed circuit board (PCB), so-called **shear mode** shock. However, it cannot be used to apply a shock in the vertical direction, so-called **pull mode** shock, as the hammer is blocked in its movement by the underlying PCB. However, it is known that the shock resistance for the joints in pull mode is lower than when they are loaded under a shear load.

In order to allow us to actually measure the joint in axial pull mode, a dedicated design is made as shown in Figure 2. A small PCB is soldered on top of a bottom PCB which has a slot with a bit larger with than the hammer. This allows the hammer to continue its movement after tearing off the top PCB. The PCB is made as stiff as possible to avoid large bending. The solderable pads have a diameter of 375µm, and are made in both solder mask defined (SMD) and non-solder mask defined (NSMD) version. In total, the assembly consists of 60 solder joints (3 rows of 10 joints at both side). In order to have a stand-off height of around 200µm, solder paste is applied at both PCB’s and a larger stencil diameter is used.

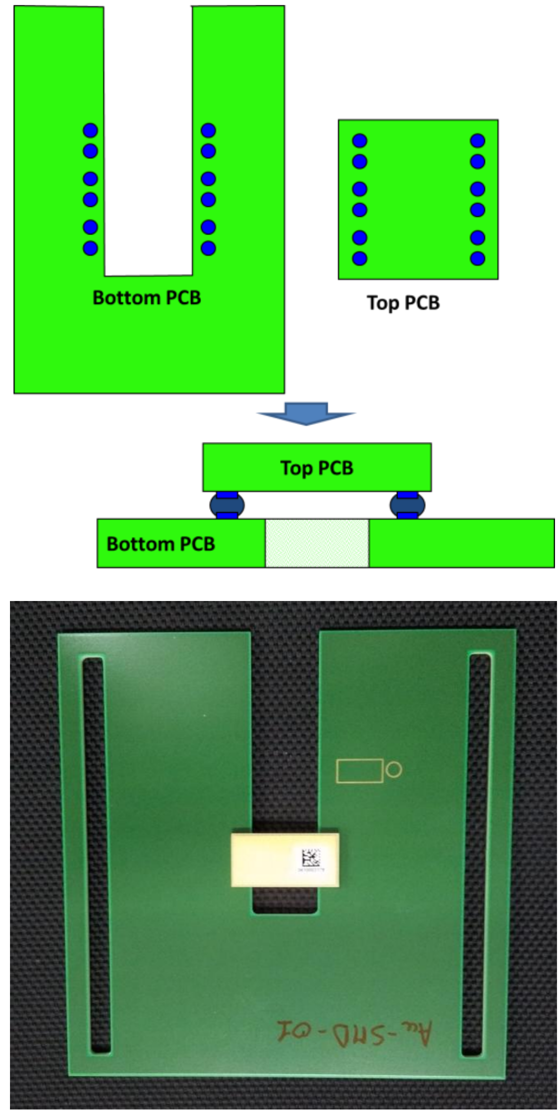

Figure 2: Schematic drawing (top) and realisation (bottom) of the concept of assembling two boards together with a slot in the bottom PCB allowing the Charpy hammer to impact the small PCB.

Thanks to the setup, the assemblies can be tested in both shear and pull mode, as shown in Figure 3.

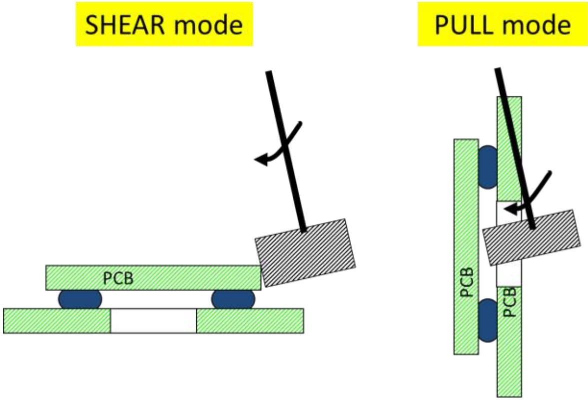

Figure 3: Schematic drawing how samples can be tested under both shear and axial (pull) shock mode.

Sample variations

For the shock testing, four different sample types have been prepared with two alternatives of the pad finish (electroless NiAu vs. immersion Sn) and the two versions of the solder mask design (solder mask defined vs. non solder mask defined). The samples are indicated as shown in table below:

Table 1: Sample variations

	SMD	NSMD
Electroless NiAu (ENIG)	*ENIG-SMD*	*ENIG-NSMD*
Immersion Sn finish	*Sn-SMD*	*Sn-NSMD*

Cross-sections of both finishes shows the expected IMC formations as listed up at the first page.

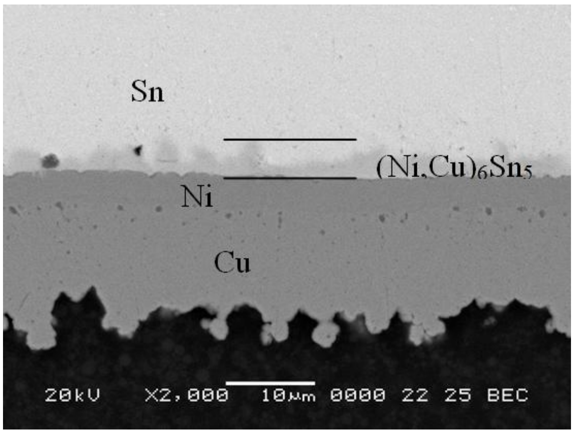

Figure 4: SEM picture of solder joint with ENIG finish

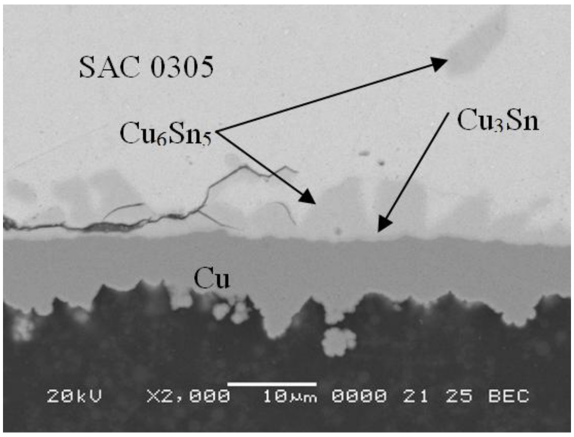

Figure 5: SEM picture of solder joint with immersion Sn finish

The samples are soldered using low Ag SAC (Sn99.2%, Ag0.3%, Cu0.5%) which is applied on both PCB's using a solder paste.

In order to see the positive or negative impact of IMC growth, assemblies have been also tested after thermal ageing (1000 hours at 150°C).

Experimental results

The results of the pull shock tests are shown in Figure 6. A obvious difference is found between the different samples types. The main trends are that ENIG has a lower absorbed energy than Sn. This confirms the trends found in literature. And as expected, NSMD has much higher energy absorption than SMD as the grip of the joint over the pad is better.

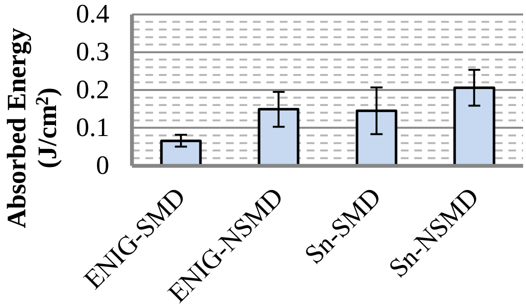

Figure 6: Energy per unit soldered area absorbed by the solder joint in the Charpy shock test (PULL mode). The samples are NOT thermally aged.

The same shock tests have been performed on the aged samples. Figure 7 shows that for all sample types, the absorbed energy is higher after thermal ageing, meaning that the joints become more shock resistant after ageing. It also proofs that the finishes are of good quality and are not inducing Kirckendale voiding nor poor IMC formation over time.

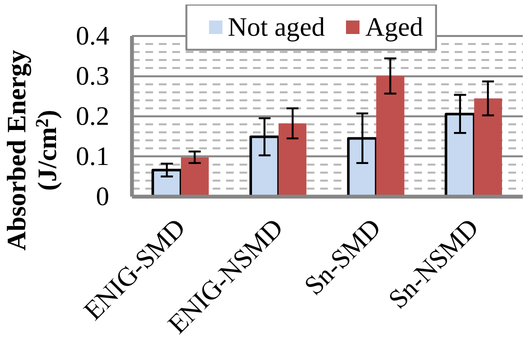

Figure 7: Showing the impact of thermal ageing (1000 hours @150°C) on the energy per unit soldered area absorbed by the solder joint in the Charpy PULL shock test.

Figure 8 compares the absorbed energy for assemblies tested under pull versus shear mode. The absorbed energy under shear mode is typically 6 times higher than for pull mode.

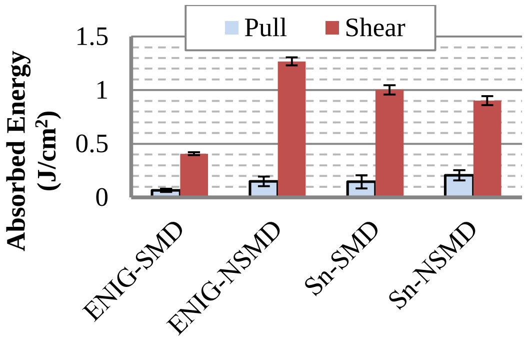

Figure 8: Comparing the shock results under shear and pull mode

Failure analysis

Cross-sectional analysis has been performed on the tested samples in order to find the fracture location. Table 2 gives an overview of the different kind of fracture locations. For ENIG, the fracture was always between the Ni and the IMC layer, also after ageing. For immersion Sn, only IMC-Cu fracture was found when the SMD pad was used. In all other cases, the fracture occurred in the FR4 below the pad, resulting in a FR4 pad cratering. This means that the real shock strength of the joint is even higher than what was measured.

Table 2: Fracture locations for different sample types

	Fracture Location	
	Not aged	**Aged**
ENIG – SMD	IMC / Ni interface	IMC / Ni interface
ENIG – NSMD	IMC / Ni interface	IMC / Ni interface
Sn – SMD	IMC / Cu interface	Pad cratering in FR4
Sn – NSMD	Pad cratering in FR4	Pad cratering in FR4

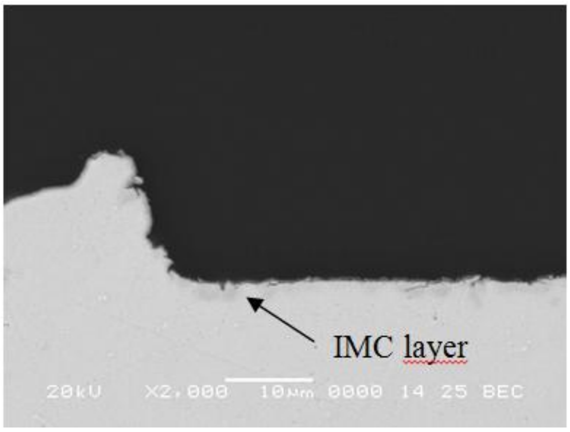

Figure 9: Example of fracture between Ni and IMC (only IMC and solder left after cracking)

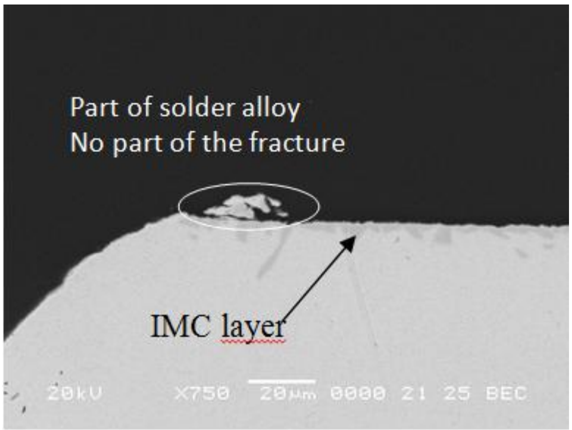

Figure 10: Example of fracture between Cu and IMC layer (only IMC and solder left after cracking)

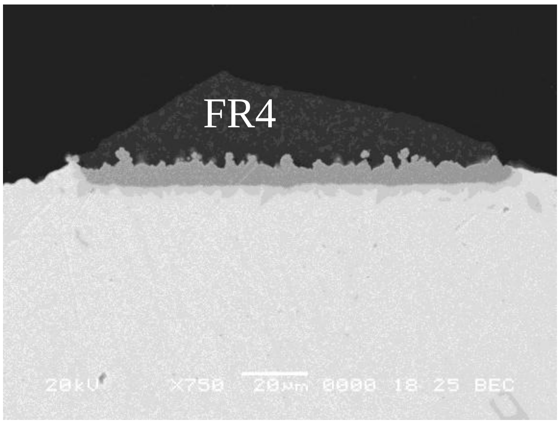

Figure 11: Example of pad cratering in underlying FR4 material after shock test

Conclusions

A unique sample construction allows us to measure the absorbed energy of a real sized solder joint under a mechanical shock test, and this under both shear and pull mode. The setup is a miniaturised Charpy system.

A first conclusion is that the solder joints loaded under shear mode can take up about 6 times more energy than when they are loaded under axial pull force. This shows that perpendicular pull stress is far more critical for solder joints than shear stress.

Comparing the two different pad finishes, we can conclude that for joints with the chosen low Ag SAC solder, the absorbed energy is lower with ENIG than for immersion Sn. Failure analysis depicted that the fracture always occurred between the Ni finish and the IMC for ENIG. For Sn finished pads, only fracture between IMC and copper was seen for SMD pad. For NSMD, the fracture occurred in the underlying FR4 material.

Thermal ageing improves the strength of the solder joint, which also indicates the good quality of the surface finishes used in this experiment. For the immersion Sn finished pads, the weakest point moved from the IMC to inside the PCB (pad cratering).

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