Commissioning of a New Solder Bumping Process for the Pixel Upgrade

Alessandro Pasquini

Università degli studi di Firenze, Italy

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Abstract

In the incoming upgrade of CMS pixel detectors the setting and the testing of the bonding process is a fundamental step to obtain high quality products. The testing provides lots of data that can be analyzed to understand in deep each variable involved.
A central question regards the structure of the bumps; they provide the electrical and the mechanical connection between the read-out chip and the detector.
In order to choose correctly the parameters of bump bonding process, it is necessary to do destructive and non-destructive tests on the samples and microscope inspections.
In my summer student lifework I have tried to help the staff of FEC group in the setting and testing of the bumping and bonding processes that should be ready by the end of 2013. In particular, I was involved in testing and inspections of the samples through destructive (grinding) and non-destructive tests and optical analysis. Moreover, I have done analysis of the data from these inspections using Matlab.

Contents

1 Introduction

The upgrade of CMS pixel detectors (fig.1a) is expected for the 2016/2017 and it will not only replace the current pixel detectors but it also will provide an additional layer of barrel and disk to improve the resolution. There will be also a reduction of material inside the tracking volume and a reduction of the dead-time of the readout chips. The pixel detectors (fig.1b) of the CMS experiment needs to be replaced after a couple of years of LHC running because of radiation damage. The luminosity after the upgrade is expected beyond 10^{34} cm^{-2} s^{-1}. About the connections of the inner detectors of CMS to the outside, they are very dense and cannot be expanded. The upgraded detector must re-use existing services for cooling, power and readout.
The FEC group is being occupied of the bonding process of the read-out chip and the sensor chip. In particular is used a method that can place single solder balls on the pads serially instead of the more common lithographic parallel process.

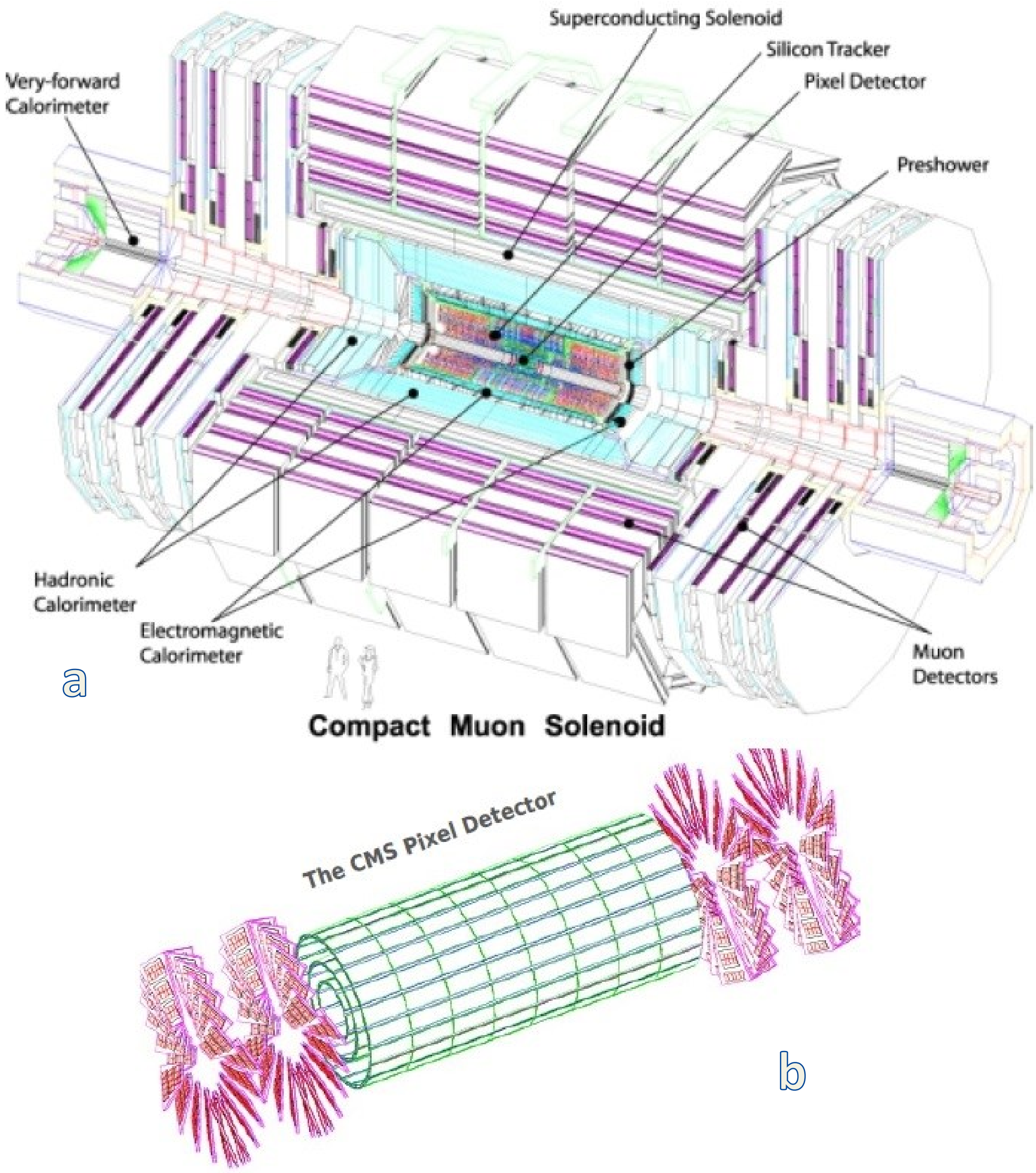

Figure 1 – a) Schematic of the structure of the CMS detector. b) Schematic of the current Pixel detector System inside the CMS Detector. Green the cylindrical Barrel. Pink the disks of the End Caps

2 Structure of pixel detectors

An elementary cell – the module - of a pixel detector is made mainly by three layers: a control electronic circuit, a sensor chip and a read-out chip ROC (fig.2). In particular, the electronic circuit is composed by a Flex-Printed High-Density-Interconnect HDI, some SMD components, the Token-Bit-Manager TBM and the power source.

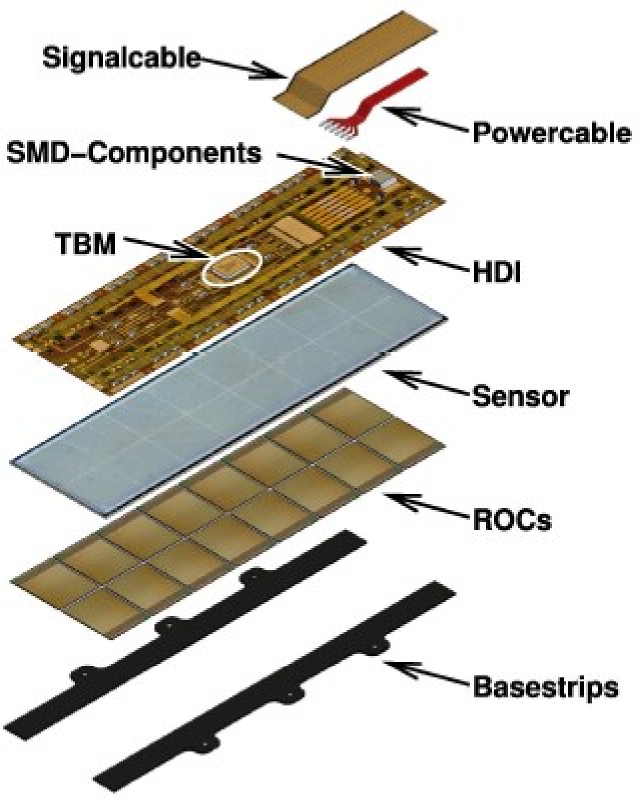

Figure 2 - Pixel Detector Module

The assembly of the read-out chip onto the sensor chip through the flip-chip bonding process is the final goal of this work.
The contact pattern of a read-out chip is based on 26 double columns and 80 rows of pixels that each are contacted individually to read the signals from the sensor.
Regarding the dummy modules used for the tests, each double column has four pads to test the resistance (two pads are for the current and two for the voltage) (fig.3).
The distance between the double columns is 300 microns and between the rows is 100 microns. The dimension of a pad is 50 microns and the aperture in the pad for the contact with the lower layer is 30 microns.

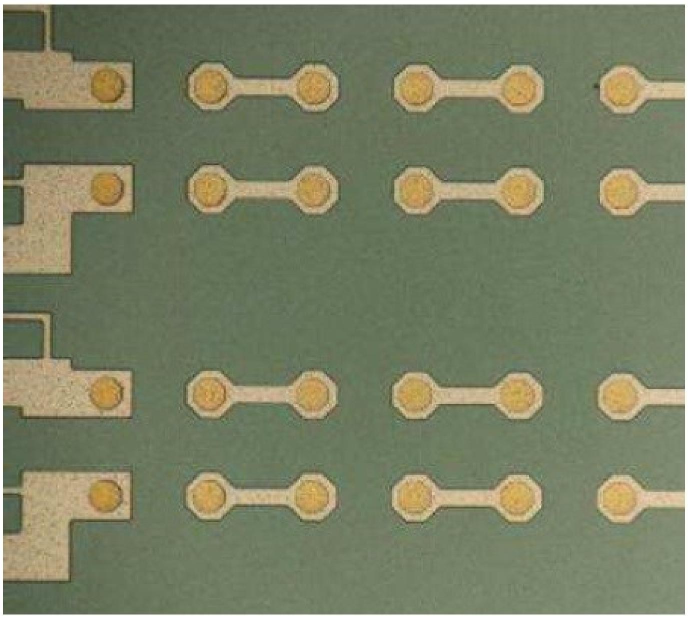

Figure 3 – Dummy Read-out chip double columns structure

In the dummy modules the contacts are joined in couples in order to verify the correct alignment after the flip-chip bonding process through electrical test (fig.4). This structure is called Daisy Chain and it is very easy in this way to measure the resistance of a chain (double column). Accordingly, it is possible to obtain the results of the flip-chip bonding process in terms of working chains. In the real chip the contacts are single and not joined like here and each pixel is read by one contact of the ROC.

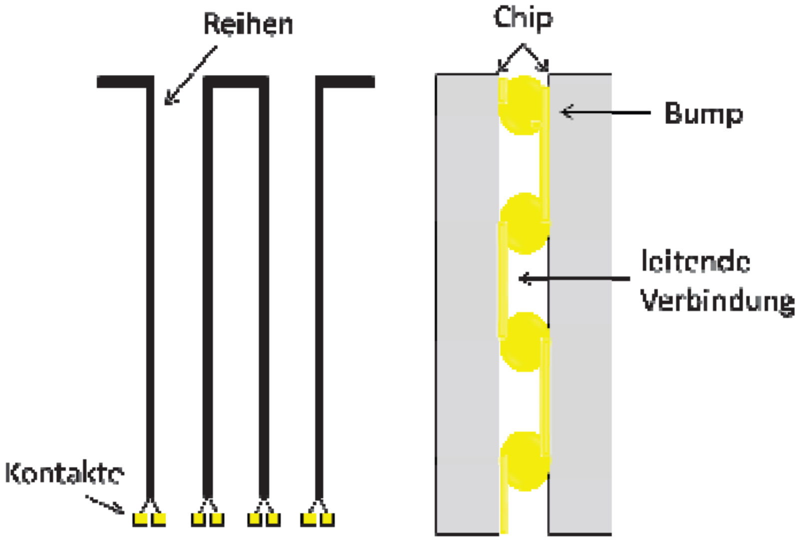

Figure 4 - Daisy Chain

3 Preparing of samples

In order to save chips during the preliminary tests each ROC Dummy was divided into two samples along a hypothetical middle line (fig.5). This is done manually by the operator with a diamond tip (scratching). After this precise initial damage it is possible to break the chip along its scratch (cleaving). For doing this it is sufficient to position a half of the chip between 2 glasses and to press the other part.
After this, the two halves need a cleaning cycle. This process consists of an ultrasonic bath at the frequency of 35 kHz. The samples are inserted in a glass recipient with IPA that is located in a water bath in the ultrasounds machine. This stimulates the wanted cleaning reactions.
Afterwards the chips have to be rinsed in DI-water and dried with forced Nitrogen.

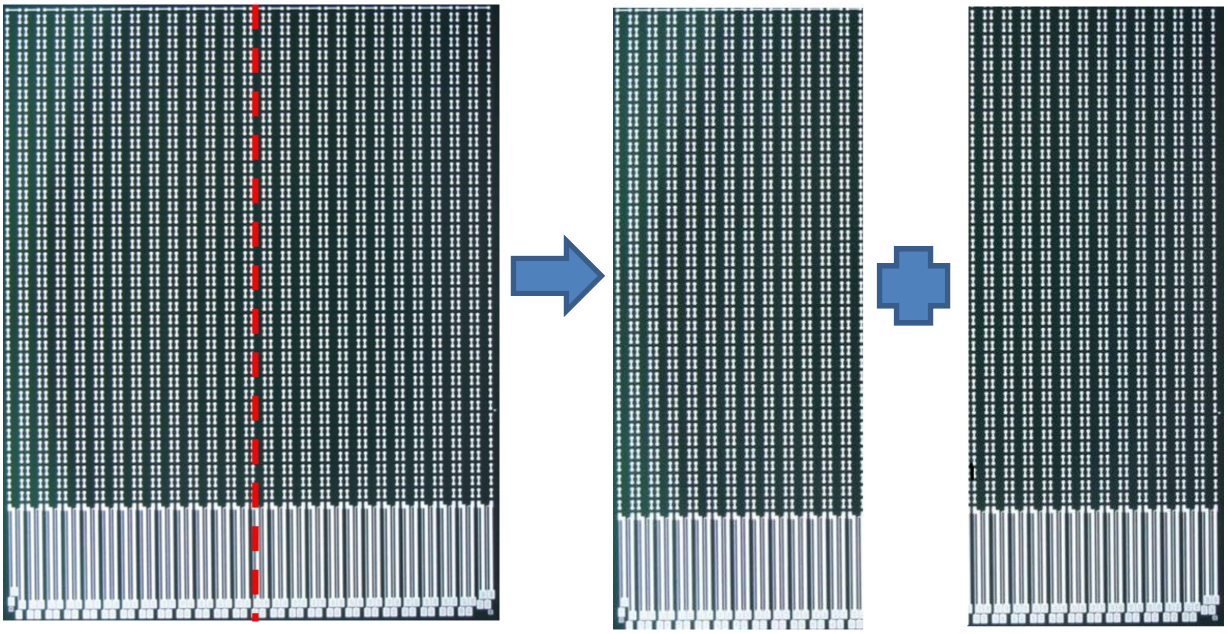

Figure 5 - Two samples from one chip

4 Bonding process

In FEC lab there is an automatic solder jetting machine that needs lots of input data to work.
At the beginning of a work-day with this machine it is mandatory to initialize the process through the insertion of some parameters as well as checking the calibrations for deviations.
It needs some cycles of calibration to stay at 1 um error or below. This precision is necessary for the dimensions of the chip and the solder balls.
The head of this machine is moved by a step command motor in the space x, y, z. It can also rotate along the u-angle. In the head there are mainly the capillary that release the solder balls and a camera that check the actual position and the state of the bumps.

In the following image (fig.6) there are plotted the most important signals: motor command, z direction, u rotation, velocity along x-direction, velocity along u-direction, the pressure of the Nitrogen.

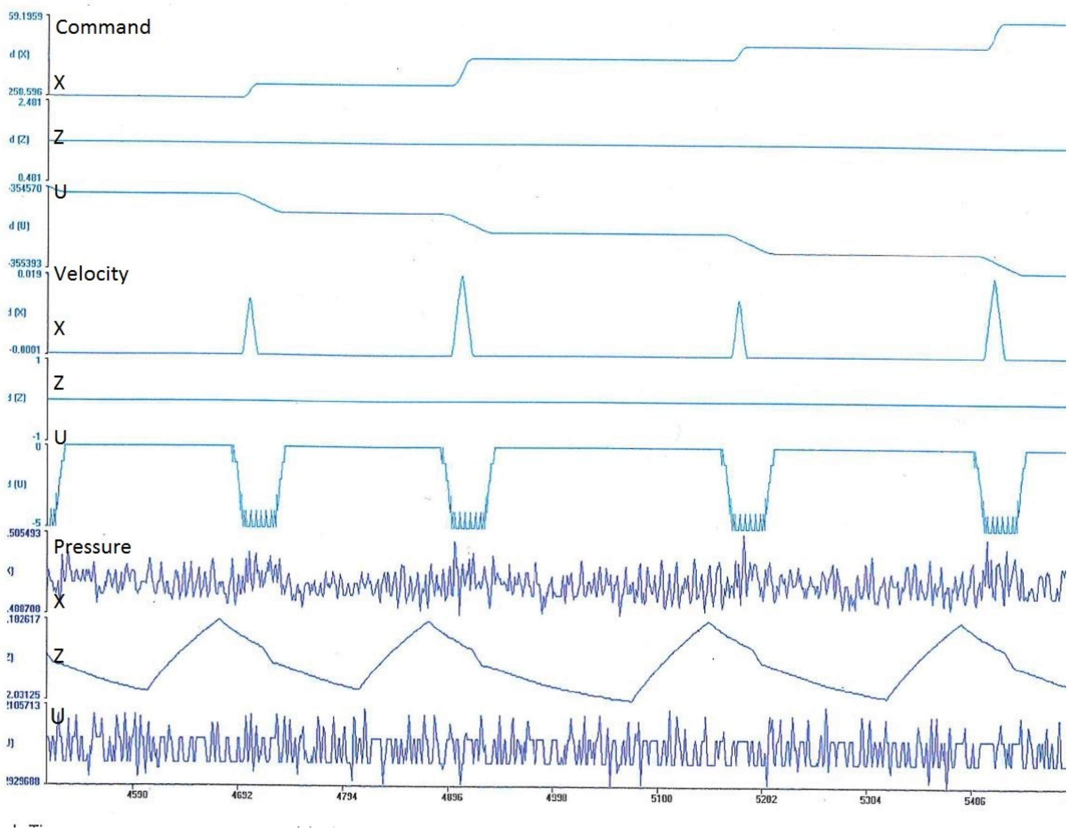

Figure 6 - Bump bonding machine signals recorded during a typical process

About the capillary that release the solder balls, it has the final part with a diameter of 37 microns. The solder balls have a diameter of 40 microns, so they cannot pass through until they are in the liquid state (fig.7). The Nitrogen flow is used to force the balls to fall down into the capillary and also from the capillary to the pad below.

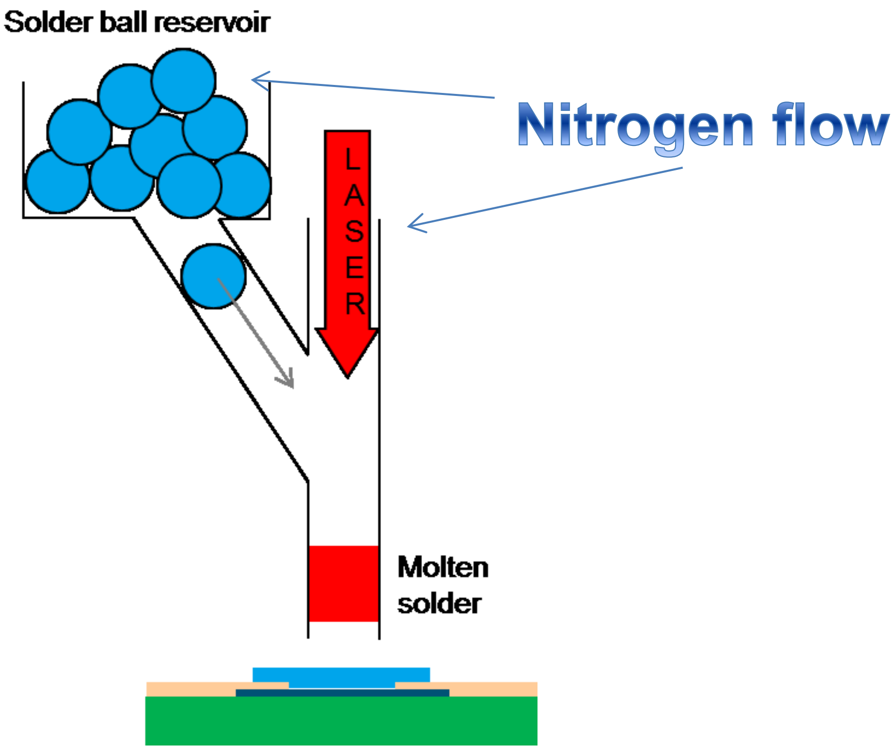

Figure 7 – Schematic of the solder jet process

For the balls detection in the capillary is used the flow of Nitrogen. About this, there are a feeder pressure limit and two thresholds: capillary blocked pressure and ball present pressure. These values are after and before the peaks in the plot (fig.6) and are useful for the machine to decide when the laser has to be used.
In the zone of decreasing pressure in the plot there is a step due to the actual release of one solder ball.
After this the ball starts to fall down. The minimum points in the pressure graph represent the moment when the sphere is at the end of the reserve box and very near to enter in the capillary. Before laser pulse we have to wait some time to be sure that the sphere is at the end of the capillary.
The most important variables that were under analysis are: the current and the pulse length of the laser, the pressure of the Nitrogen.
After the splitting of the chip, there are two samples with 80 rows divided in 4 fields of 19 (plus 1 for margin) and 10 double columns used (fig.8).
For each field there is a different combination of parameters to try to find the right solution and to understand where the interval of good operation of the machine is.

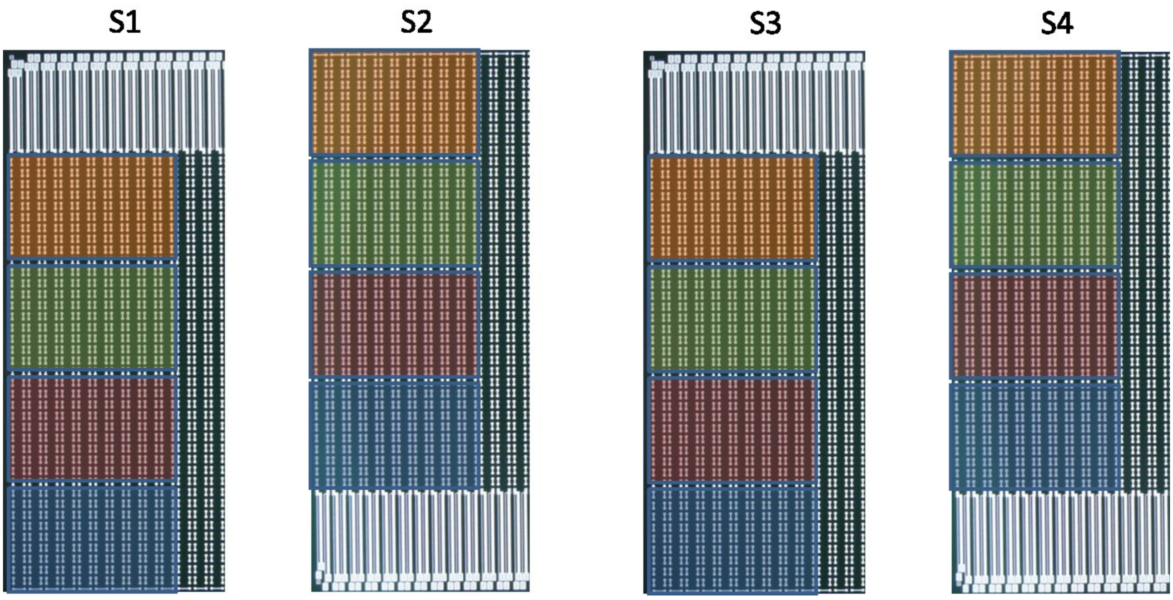

Figure 8 - Samples Structure. Each sample consists of four fields for a different set of parameters each.

The machine needs to know the space where it will move. For this purpose it is useful to program the metric: the start point and the end point and all relative positions of the pads from these points to place the balls.
For the alignment it is enough to take two points as reference and teach in these positions of the actual sample.
The start of the experiment was with these parameters: 160 mbar feeder pressure, 145 mbar ball presence pressure, 148 mbar capillary blocked pressure, 2100 mA laser current and 0,3 ms pulse length.
But the machine was blocked after the first try and it was necessary to execute several cleaning cycles. So the next step was to try other parameters. Instead of 0,3 ms it was used 0,5 ms (tab. 1 to 4).
From the log file is possible to read the parameters of the process like the live frequency, the start time and the stop time for each field.
The average frequency is calculated considering the time between the first bond and the last bond and contains also the time needed for cleaning cycles.

Sample	1			
Field	1	2	3	4
CC	2	0	0	0
NB	2	0	0	0
Laser current [mA]	2100	2100	2100	2100
Laser pulse length [ms]	0.4	0.6	0.7	0.5
Feeder pressure [mbar]	160	160	160	160
Average frequency [Hz]	4,175824176	4,578313253	4,578313253	4,418604651

Table 1 - Sample 1 Parameters

Sample	2	2	2	2
Field	1	2	3	4
CC	0	1	0	0
NB	0	2	0	0
Laser current [mA]	1900	2000	2200	2300
Laser pulse length [ms]	0.5	0.5	0.5	0.5
Feeder pressure [mbar]	160	160	160	160
Average frequency [Hz]	4,52381	4,042553	4,175824	4,269663

Table 2 - Sample 2 Parameters

Sample	3			
Field	1	2	3	4
CC	0	0	0	0
NB	1 (bad bump->dirty chip maybe)	0	0	0
Laser current [mA]	2100	2100	2100	2100
Laser pulse length [ms]	0.4	0.5	0.6	0.7
Feeder pressure [mbar]	180	180	180	180
Average frequency [Hz]	4,810127	4,691358	4,691358	4,935065

Table 3 - Sample 3 Parameters

Sample	4			
Field	1	2	3	4
CC	0	0	0	0
NB	0	0	0	0
Laser current [mA]	1900	2000	2200	2300
Laser pulse length [ms]	0.5	0.5	0.5	0.5
Feeder pressure [mbar]	180	180	180	180
Average frequency [Hz]	4,810127	4,75	4,810127	4,634146

Table 4 - Sample 4 Parameters

5 Microscope and laser inspection

In order to inspect the samples it has been used an optical microscope.
In these inspections were used ten (fig.9a) and fifty time magnifications to try to obtain the greatest possible amount of information (fig.9b).

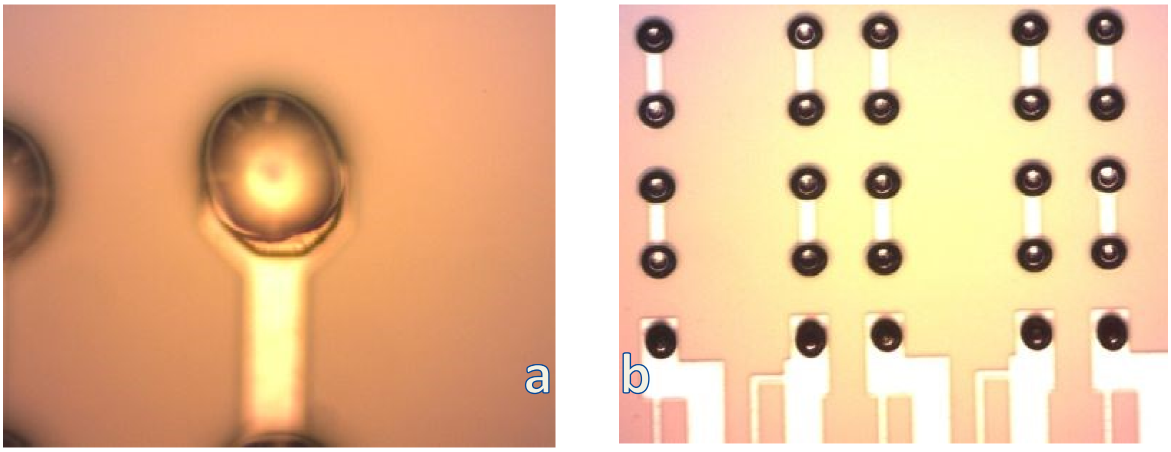

Figure 9 a, b – Optical Microscope Inspection. a) Single bump in higher magnification. b) Overview picture of several bumps to gain information about shape regularity within this group of bumps

Also the Laser Scan Microscope can use different magnifications for data acquisition. Here we scanned areas that each contained four bumps.
The images contain laser metrology information as well as standard optical microscopy pictures that are overlain (fig.10 a, b). It is possible to gain height information from the profile view that presents laser scanning measurement results (fig.10 c).
It is possible to see in the following image some artifacts due to the reflections of the sides of the bumps. This leads to an untrusted measure of the diameter.

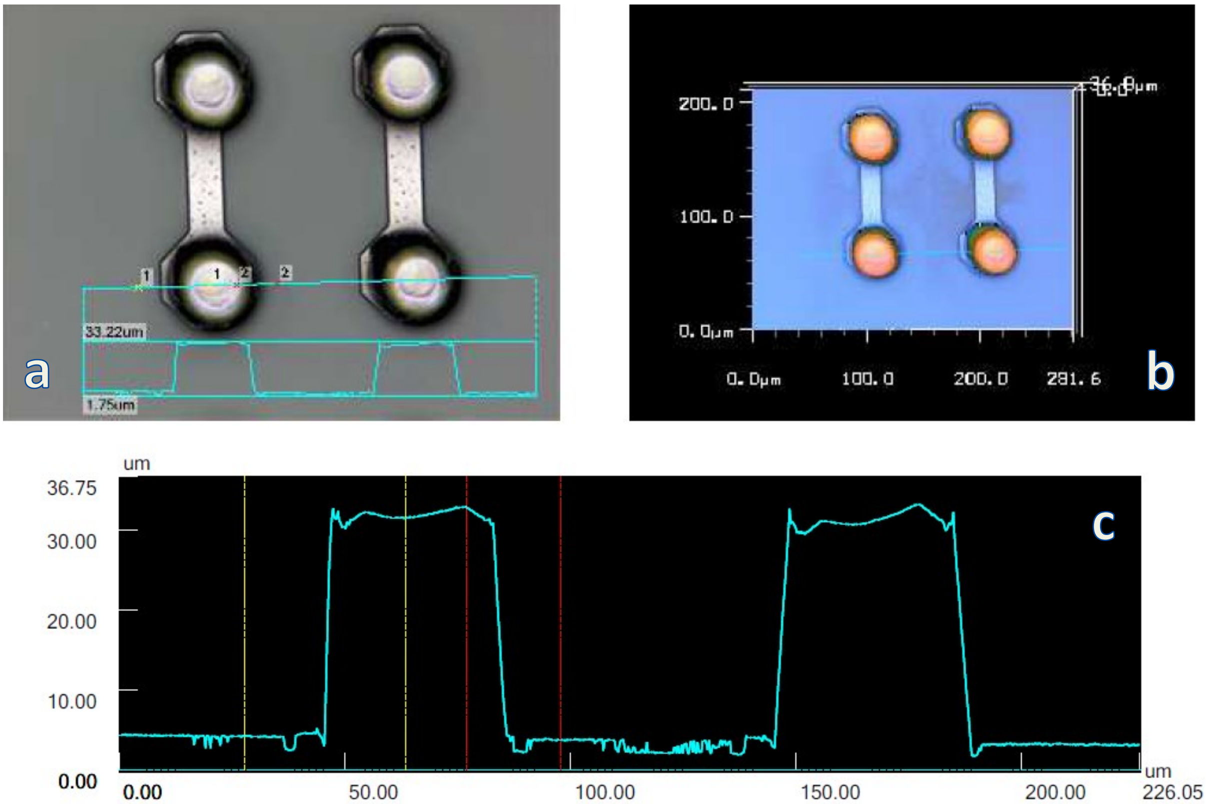

Figure 10 - Scanning Laser Microscope Pictures: a) Laser intensity + color picture b) Height picture after processing c) Profile of reflections along a set segment

It was also possible to do an inspection with the scanning electron microscope but it did not give more information respect to the laser and optical microscope inspections except for the bumps diameters. Moreover this kind of scan requires more time than the others (fig.11). But this investigation method could bring additional information in later inspections about the intermetallic phases that build up during the liquid phase of the solder.

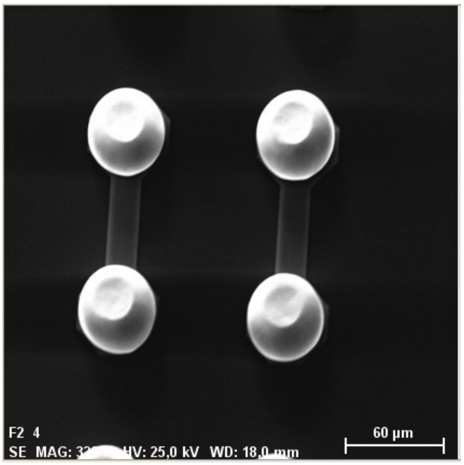

Figure 11 – Scanning Electron Microscope Picture

After this kind of inspections it was possible to say that the more energy is used, the better are the results but after a while there is a kind of “saturation” of the shape of the bumps.
So it is un-useful to spend more energy over this kind of threshold and with this choice it is possible to save machine part lifetime and to save time of the process.
In fact it was chosen one of the shortest pulse length for the laser (0.5 ms).

6 Grinding

After the inspections with the laser and the optical microscope, it is useful to have a view of the cross-section of the bumps to see if the alignment and the shape are right. In order to do this it is necessary to embed the samples in a cylinder of epoxy resin. This material becomes hard like the silicon. We need this property for grinding this test object in uniform mode. Before this process it is useful to add a label (self-sticking paper) on each sample with its name. Then it is possible to go on with the process using a vacuum box. This box is used to avoid air bubbles in the epoxy resin with the sample.
After this process it is necessary to wait for 12 hours to have a ready sample. At this moment it is possible to remove the plastic box of the sample and to go on with the cleaning through IPA. Then the sample is ready for the grinding process.
It is necessary to start with the roughest grinding paper (number 800) to level the top surface of the resin cylinder. This first step is necessary to have a uniform pressure on the sample given by the grinding machine.
After this, it is possible to start with the real grinding process of the sample. First of all, it is mandatory to start with a quite rough grinding paper (number 1200) to remove

the resin until the surface of the embedded sample. Then it is possible to use finer grinding plates like the diamonds plates.
It is very important to check with an optical microscope the actual situation after each step. Before the microscope inspection it is mandatory to clean the sample with a cycle of water, drying with Nitrogen, IPA, drying with Nitrogen.
There is a fundamental point for this machine: between two different kind of grinding processes it is very important to clean the machine to avoid deposition of larger grains of the previous step onto the grinding cloths of the following steps.
Coming back to the grinding process, when a row of bumps is reached, it is possible to use a fine grinding plate using a lubrication solution that incorporates 9 microns diamonds (Allegro largo 9 micron for about 30 seconds).
In the proximity of the cross section of the bumps, it is recommended to change to the first polishing plate using a lubrication solution that incorporates 3 microns diamonds.
The last step is a fine polishing utilizing a plate with thicker cloth and a white solution that contains a water-based soft etching solution incorporating colloids of silica particles of 0.5 micron.
The water for cooling and lubrication is used only with the grinding papers.
There are several ways to arrive at the same point (in the middle of a row).
For example:
Grinding machine with 320 paper for the upper layer of the samples to level it (10 sec). Other 10 s with 800 paper. The other side (of the cylinder) with 1200 paper for 90 sec. It is necessary to use a new grinding paper after 2 cycles of 30 seconds to maintain the same characteristics.
Green plate with the diamonds liquid of 9 micron (20 s) and then the light blue cloth with the diamonds of 3 micron (40s). At the end is used the cleaning plate.
It was used an optical microscope for taking pictures of the sample´s bumps with a magnification of 100x and the digital camera for the acquisitions (fig.12).
This is useful to see inside the bumps, in particular to see if there are reactions between the Sn-Ag-Cu bump and the Under Bump Metallization (composed by 5 microns thick layers of Ni, 200 nm of Pd and 50 nm of Au).

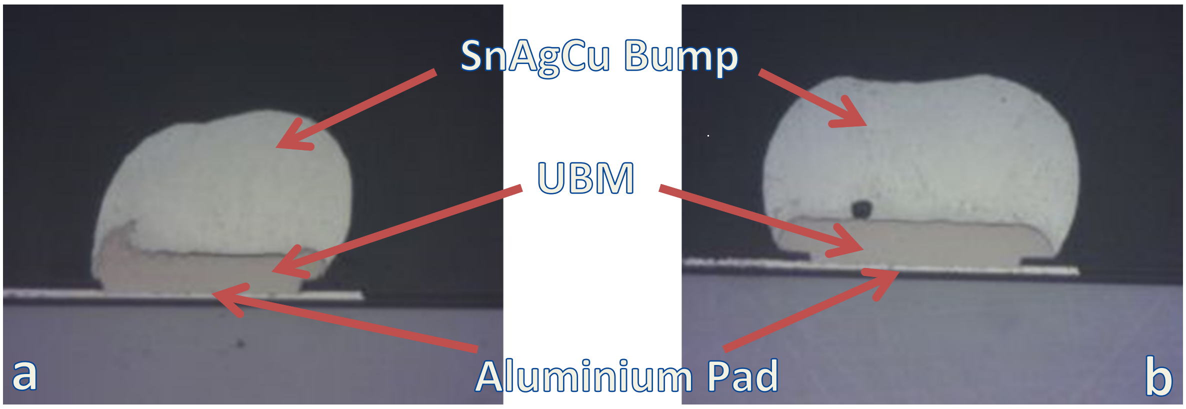

Figure 12 - Bumps cross-section pictures after the grinding process obtained with optical microscope inspections: a) Here there are interactions between the UBM pad and the metal bump b) Here there is a better shape of the bump but no interactions. The black point can be dirty on the chip.

7 Reflow and flip chip bonding

Figure 13 - Reflow Temperature Profile. There are two cleaning steps at elevated temperature for activation but still below melting point of the solder bumps. The first vertical line indicates the start of liquefaction and the second line indicates the start of the solidification of the bumps. This interval is use to obtain a good rounded shape of the bumps.

The Femto-machine is used for the reflow process and the flip chip bonding process. It has been tested on some commercial samples that have pads of the same dimensions of the real pads of the ROC (50um).

For the positioning of the detector on the read-out chip it is necessary to set the force and temperature and other parameters of placement in the thermo-compression process.

For the reflow process it is used a profile of temperature (fig.13) with some steps to activate the chemical reactions: removing the oxidation on the bumps and melting the solder balls to have rounded shape. Each step is long 20-30 seconds.

During the first two steps is used a flux of formic acid to “clean” and -for prevention of further is oxidation- there is a Nitrogen flux.

The shown parameters have been used for the new samples. The first sample of these was an entire chip completely bonded and the other two were two halves chip completely bonded (10 double columns for each sample).

The reflow parameters were varied for these chips to try to understand which could be the correct set of parameters to follow.

8 Tests

For the reflowed samples it has been done optical inspection (fig.14) and laser scans (surface and height of the bumps) in order to obtain data about the surface and the height of the reflowed bumps (fig.15 a, b, c).

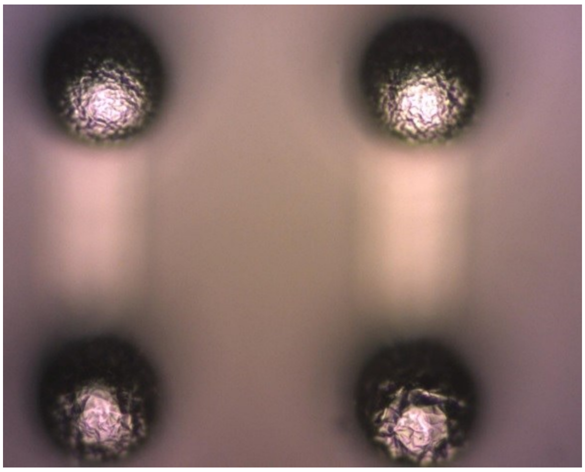

Figure 14 - Optical Scan after Reflow

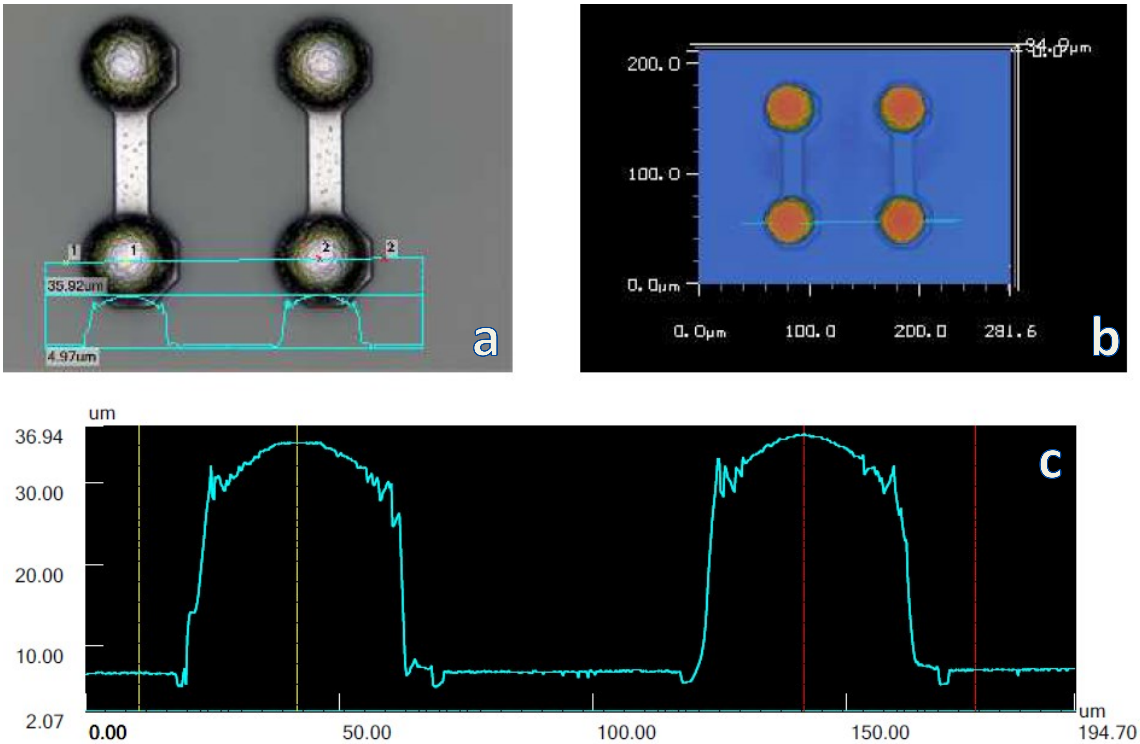

Figure 15 - Laser Scan after Reflow: a) Laser intensity + color picture b) Height picture after processing c) Profile of reflections along a set segment

Also embedding and grinding process with optical inspections were necessary to see the results in terms of chemical reactions after the reflow in the cross-section of the bumps (fig.16).

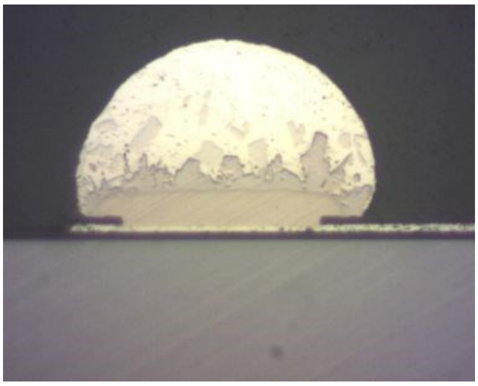

Figure 16 - Chemical Interactions inside a Bump. This is after the annealing reflow at 240°C for 25 seconds.

It is also useful to collect lots of pictures of the samples to be able to do a kind of statistic with Matlab about the height of the bumps.
It has been done a first analysis with 100 points (fig.17) and the results in terms of average value and standard deviation are very good. This has been done on the Sample R1 and then also on the others two Samples (T1 and T2). In these cases it has been done the analysis on 40 points (fig.18 to 19) per each sample. We found all bumps in the same height as expected. The standard deviation is about 400 nm only.

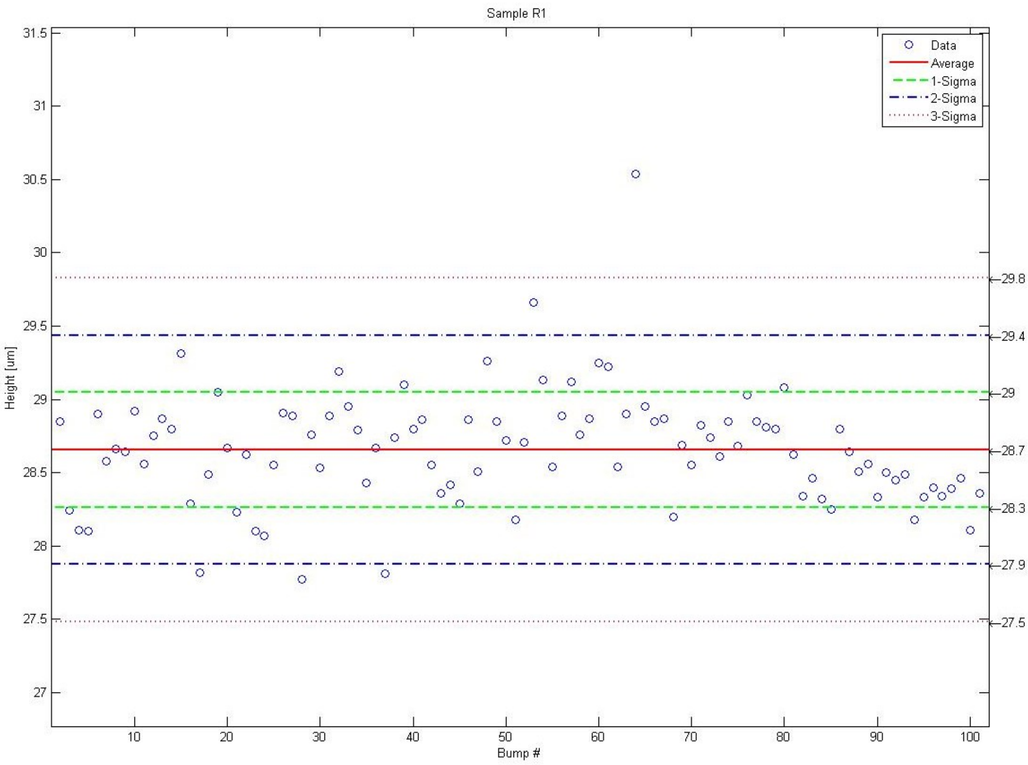

Figure 17 - Statistic Analysis of 100 Bumps of Sample R1

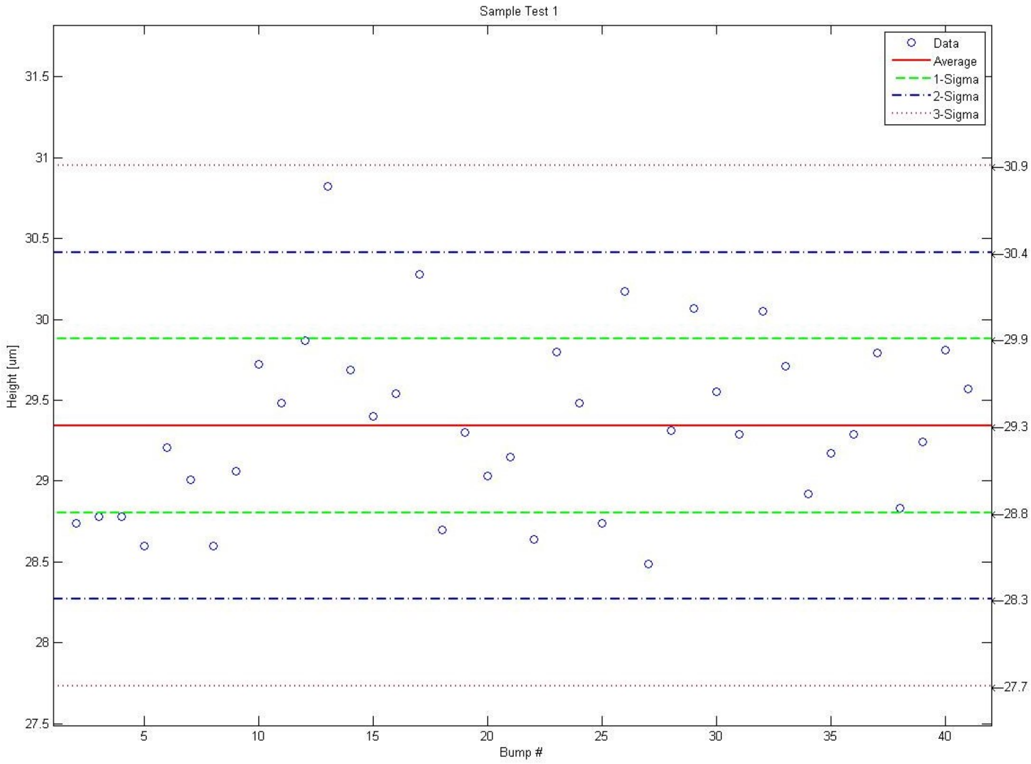

Figure 18 - Statistic Analysis of 40 Bumps of Sample T1

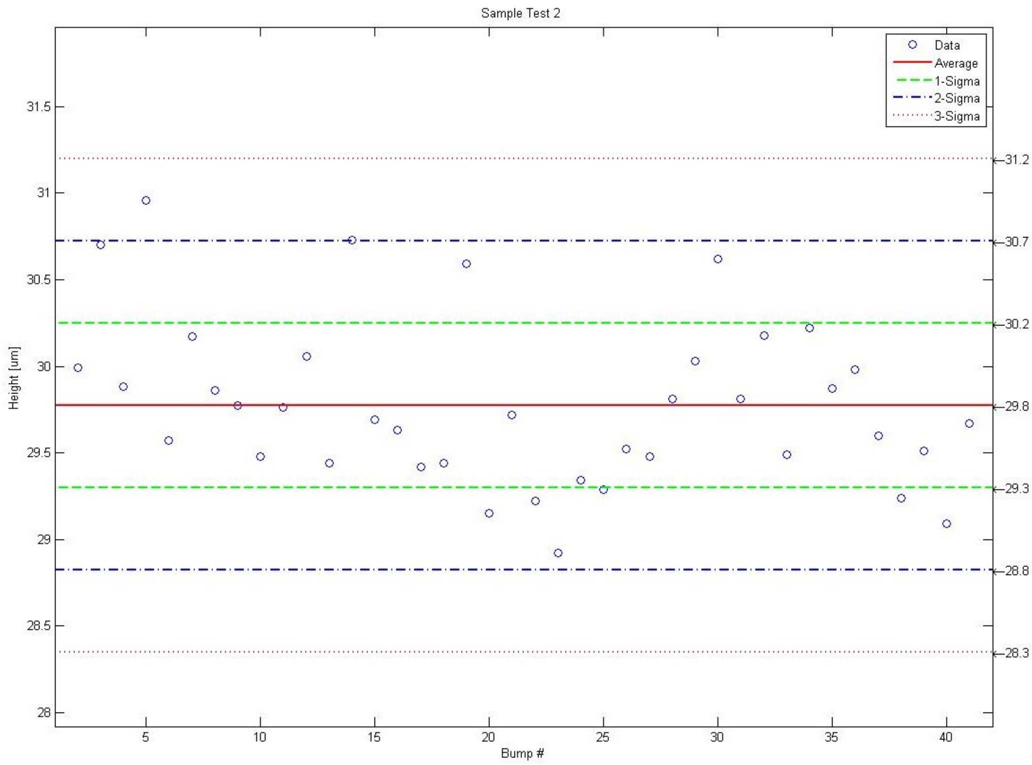

Figure 19 - Statistic Analysis of 40 Bumps of Sample T2

9 Results

From the several tests, inspections and analysis it is possible to say that there is a set of optimal parameters concerning the bump bonding process with which it is possible to go on. In particular, there is an interval of energies for the laser pulse (fig.20) that works well.

Sweet Spot:
0.64 mJ to 0.77 mJ per Pulse

	Energy in mJ			
Pulse duration in ms	1900	2000	2100	2200
0,4	0,1188	0,2106	0,3126	0,4158
0,5	0,3985	0,51325	0,64075	0,76975
0,6	0,6782	0,8159	0,9689	1,1237
0,7	0,9579	1,11855	1,29705	1,47765

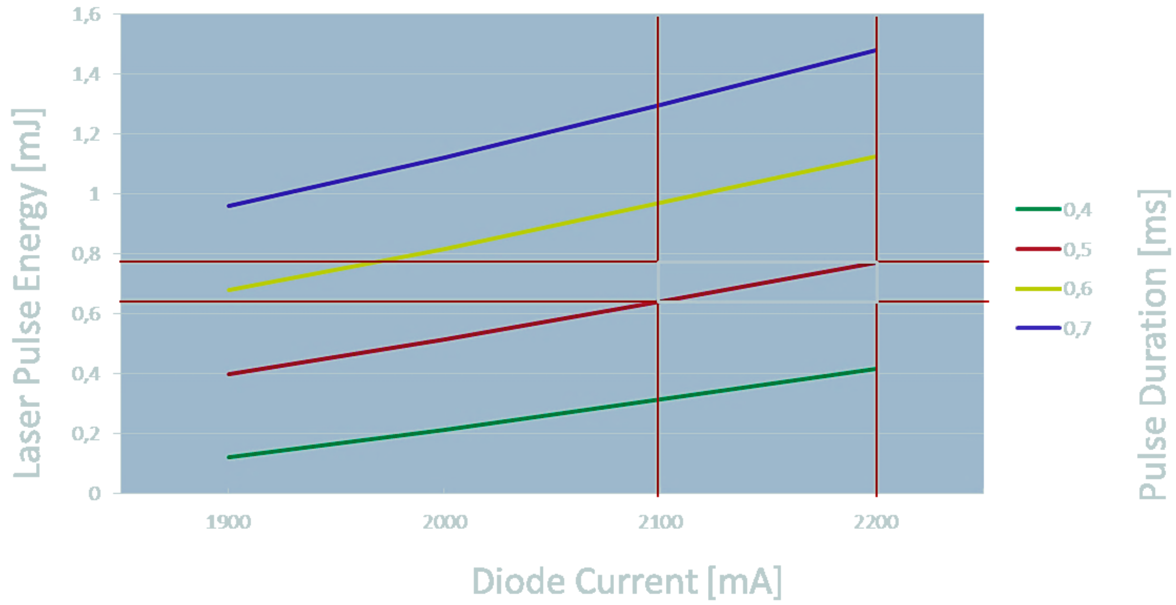

Figure 20 - Laser Energies Interval

About the feeder pressure for the same process, it has been found a good value (180 mbar) as indicated in the previous pages.
With these conditions it has been obtained the very good average speed of 4.8 Hz in the solder balls placement.
In order to obtain a very uniform bump bonding process is necessary to set very carefully the automatic machine, especially to avoid offset in placement of solder balls.
Regarding the reflow process, the last profile of temperature produced good quality bumps ready for the flip chip bonding.
Concerning the flip chip bonding, it is not properly subject of this work, but it is possible to say that this process is near to be ready.