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Analysis of Ball Soldering Parameters on the Properties of a BGA Packaged Semiconductor

Dario G. Rosa[a], Marcio R. Stracke[b], Victor T. Padilha[b], Celso Peter[a], Willyan Hasenkamp Carreira[a], Carlos Alberto Mendes Moraes[a]*

[a]Escola Politécnica, Universidade do Vale do Rio dos Sinos, São Leopoldo, RS, Brazil
[b]HT Micron - Engeneering, São Leopoldo, RS, Brazil

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Integrated circuits have several applications, including medicine and the aerospace industry, where reliability is essential. Packaging is an important step in the manufacturing of integrated circuits, and ball soldering is one of the most critical process, especially in assembling and interconnecting integrated circuits. The solder joint formed during the ball soldering process is intrinsically associated with the performance and the reliability of the electronic system. This study analyzed the influence of parameters or factors affecting the ball soldering process from the perspective of intermetallic compound formation and shear stress of the solder joint. The results indicate there is an interaction coupling between these two factors that cannot be seen when they are investigated individually, meaning that the individual effect of each factor differs from that of the combinations of factors. The results showed that the factor that most influenced shear stress and thickness of the intermetallic compound was peak temperature during ball soldering.

Keywords: *Ball grid array packaging, intermetallic, shear stress, soldering.*

1. Introduction

In addition to consumer goods, integrated circuits (ICs) have several important applications such as medicine, aerospace, and military industries. Therefore, a reliable performance of ICs is essential. While a desktop computer failure in an office, for instance, may cause some degree of inconvenience, a malfunction in a pacemaker may be fatal[1].

The assemblage of an IC includes several steps, the last of which is the back-end, also referred to as packaging[2]. One of the most common packaging technique used for high performance scenarios is the ball grid array (BGA), which is preferred when considerable thermal and electric requirements are involved. For this reason, BGA is used in a variety of devices, such as microprocessors and computer memory[3].

One of the process steps in BGA is ball soldering, which performs a crucial role when assembling and interconnecting ICs. As a bonding material, solder enables electric, thermal, and mechanical continuity in the assembly of electronic devices[4]. The solder joints formed during the process are intrinsically linked with the performance of ICs and the overall reliability of an electronic system[5].

One of the most important mechanical properties of solder is its creep-fatigue behavior. Most solder alloys have low shear stress values, compared with tensile and compressive strengths. In addition, solder alloys are subjected to shear stress during operation. These factors underscore the importance of investigating the mechanical property of solders[6]. Another relevant parameter is the formation of intermetallic compounds, which warrants good metallurgical connection[7]. Intermetallic compounds also delay signals and reduce the operation voltage of electrical components, since their electrical characteristics like high ohmic resistance may negatively affect electron flow[8].

If the connection between solder balls and the substrate is not satisfactory, problems like sphere detachment during transportation or use, interrupted operation during electrical tests, and overall malfunction of the device may be observed[7]. In addition, aspects like performance and quality of solder are central to the integrity of a solder joint, which are vital to the appropriate operation of the assembly as a whole[4].

Research has been done to investigate soldering parameters such as reflow cycles, preconditioning, time and temperature[9,10], as well as the usage of nanoparticles[11,12] and flux quantity[13] and their impact on the overall reliability. However, we could not find research addressing flux quantity against temperature profiles during the ball soldering process.

In this context, the present study analyzed the influence of the amount of solder flux dispensed and temperature profile of the oven during the ball soldering process on the thickness of the intermetallic compound formed and on shear stress on the interface between solder joints between balls and the substrate of a BGA packaged semiconductor device.

This investigation identified the combination of factors that produced the best result in terms of supporting higher shear stress and inducing the growth of thin intermetallic layers, and may help to solve reliability issues in the electronics manufacturing industry.

*e-mail: cmoraes@unisinos.br

2. Materials and Methods

The experiments carried out to evaluate the temperature profile and the amount of solder flux used during the ball soldering process were carried out as described in Figure 1.

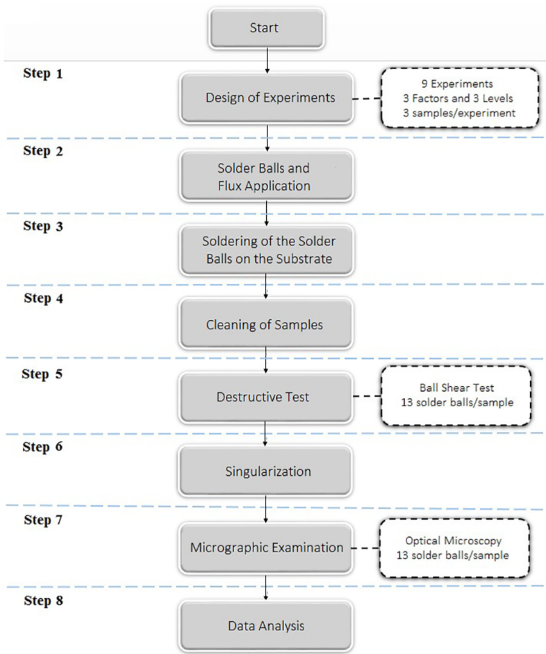

Figure 1. Flowchart showing the experiment stages.

The effect of the temperature profile and amount of solder flux on the thickness of intermetallic compound and on shear stress of the solder joint formed between the ball and the substrate were analyzed according to three factors, each factor with three levels. The factors that most influenced the characteristics measured were four, among which those that could be measured or vary during the process. The experiments were devised according to the Taguchi method. The experimental design obtained showing the required experiments and the levels of each factor are shown in Table 1. Three samples were used in each experiment.

Shear stress was assessed based on destructive assays called solder ball shear tests, as in JESD22-B117B. Since shear stress may be influenced by these parameters, the assays were conducted using the same cutting tool and identical values of shear speed, retraction tool height, and solder reflow time so as to afford a valid comparison of the results[14]. The tests were carried out using a multipurpose bondtester (4000, Nordson Dage). Microsection analysis was adopted to investigate the thickness of the intermetallic compound using an optical microscope (CX31, Olympus).

All experiments were conducted using fiberglass-reinforced epoxy (FR4) substrates plated with electroless nickel immersion gold (ENIG). The samples were assembled with a water-soluble solder flux and 0.45 mm ± 0.05 mm lead-free solder balls with 96.5% Sn, 3% Ag, and 0.5% Cu (melting point between 217ºC and 220ºC).

3. Results and Discussion

Shear stress of solder joints was evaluated using destructive assays. Figure 2 shows the fracture surface of a solder interface in a ductile solder sample (a) and the fracture obtained in the present study after the shear stress test (b).

Figure 3 shows the distribution of shear stress data of each experiment. All experiments presented different mean shear stress values. The Analysis of Variance (ANOVA) showed that the mean shear stress values of at least two experiments were significantly different.

Table 1. Orthogonal array with nine experiments and levels of each factor.

Experiments	Peak Temperature ºC	Pre Heating Rate ºC/s	Number of Solder Flux Applications
1	243	1.82	1
2	243	2.24	2
3	243	1.44	3
4	255	1.82	2
5	255	2.24	3
6	255	1.44	1
7	234	1.82	3
8	234	2.24	1
9	234	1.44	2
Levels		Factors	
	Peak Temperature ºC	Pre Heating Rate ºC/s	Number of Solder Flux Applications
1	243	1.82	1
2	255	2.24	2
3	234	1.44	3

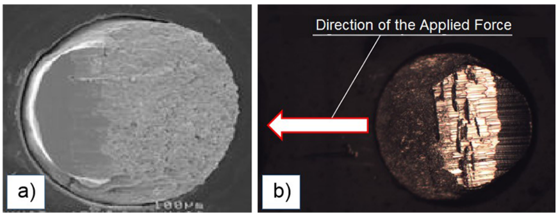

Figure 2. Surface of terminal solder fracture to afford a valid comparison of results of a sample after the solder ball shear stress test.

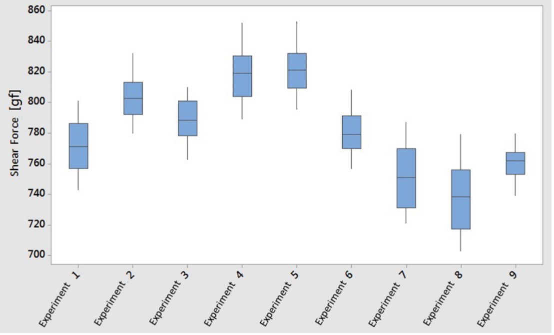

Figure 3. Shear stress maximum, minimum, and interquartile values.

The results also show that the most influential factor, not considering interactions, was peak temperature, followed by the amount of solder flux (here, the number of solder flux applications), and preheating rate. Shear stress values also increased with peak temperature and preheating rate. However, it was not possible to detect any relationship between the number of solder flux applications and shear stress. Two applications induced higher shear stress, compared with one application. However, two applications promoted lower shear stress values, compared with three. The levels of each factor that presented the highest shear stress value were peak temperature of 255ºC, followed by three applications of solder flux, and preheating rate of 2.24ºC/s. This combined loading setting had a shear stress of 825 gf. Figure 4 shows the interactions for shear stress, revealing interactions between the factors that, when combined, did not present the same behavior observed separately.

The experiment was conducted again considering the peak temperature of 255ºC, three applications of solder flux, and preheating rate of 2.24ºC/s, shear stress was 821.48 gf. The higher the strength required to shear the sample, the higher its resistance and, therefore, this combination of levels of factors used in the experiment provides the highest shear stress to the solder joint formed between the solder ball and the substrate.

Thickness of intermetallic compound was evaluated according to micrographic assays. The intermetallic compound is shown in Figure 5.

The distribution of intermetallic compound thickness is shown in Figure 6. As before, ANOVA confirmed that the mean thickness of the intermetallic compound of at least two experiments was significantly different.

Also, when the thickness of the intermetallic compound is analyzed as a function of peak temperature, preheating rate, and number of solder flux applications, no relationship was observed with the increase or decrease of levels of each of these factors. The factor that most influenced thickness, without considering interactions, also was peak temperature, followed by the number of solder flux applications.

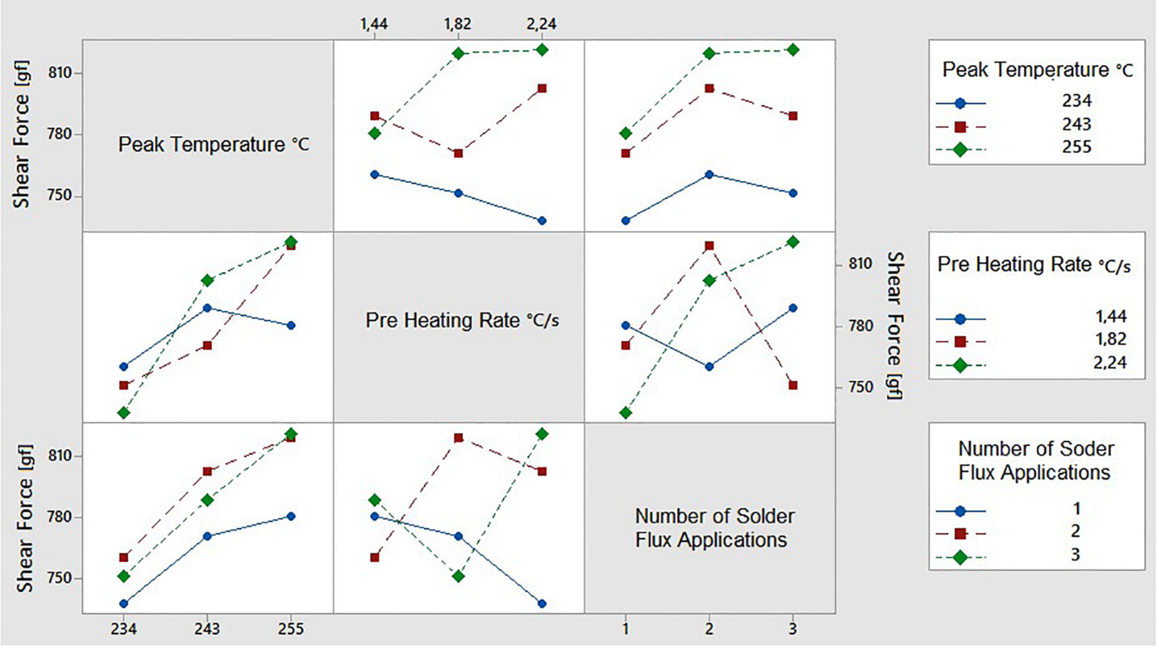

Figure 4. Shear stress interactions.

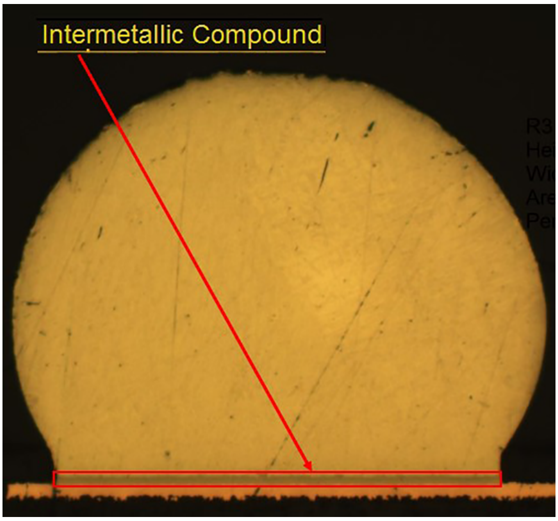

Figure 5. Intermetallic compound formed between the solder boll and the substrate (00x).

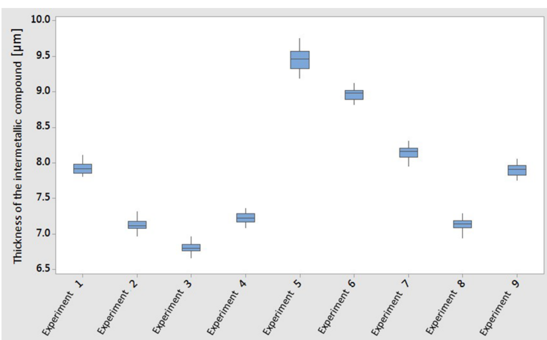

Figure 6. Shear stress maximum, minimum, and interquartile values of thickness of intermetallic compound.

Figure 7 shows the interactions between thickness of the intermetallic compound and the other factors. Interactions were observed between factors that, when combined, did not exhibit the same behavior observed when analyzed separately. For example, considering one application of solder flux, increasing peak temperatures led to a thicker layer of intermetallic compound. In turn, thinner intermetallic compound layers were formed when higher preheating rates were used. The combination that promotes the formation of the thinnest intermetallic compound layer, which was 6.5 µm thin, was temperature of 243ºC, three applications of solder flux, and preheating rate of 1.44ºC/s.

The experiment was conducted again with peak temperature of 243ºC, three solder fluxes applied, and preheating carried out at 1.44ºC/s, the thickness of the intermetallic compound was 6.81 µm. This combination of levels for each factor produced the best result, since it induced the thinnest layer of intermetallic compound between the solder ball and the substrate. Excess intermetallic compound may affect the solder joint negatively, given that cracks are often observed around this interface under stress conditions[8]. A thick layer of intermetallic compound is also undesired due to the fact that its high electrical resistance may affect electron current[15].

The results of the present study may be generalized to all types of packaging based on FR4 substrates plated with ENIG, assembled with a water-soluble solder flux and lead-free solder balls SAC (Sn, Ag, Cu).

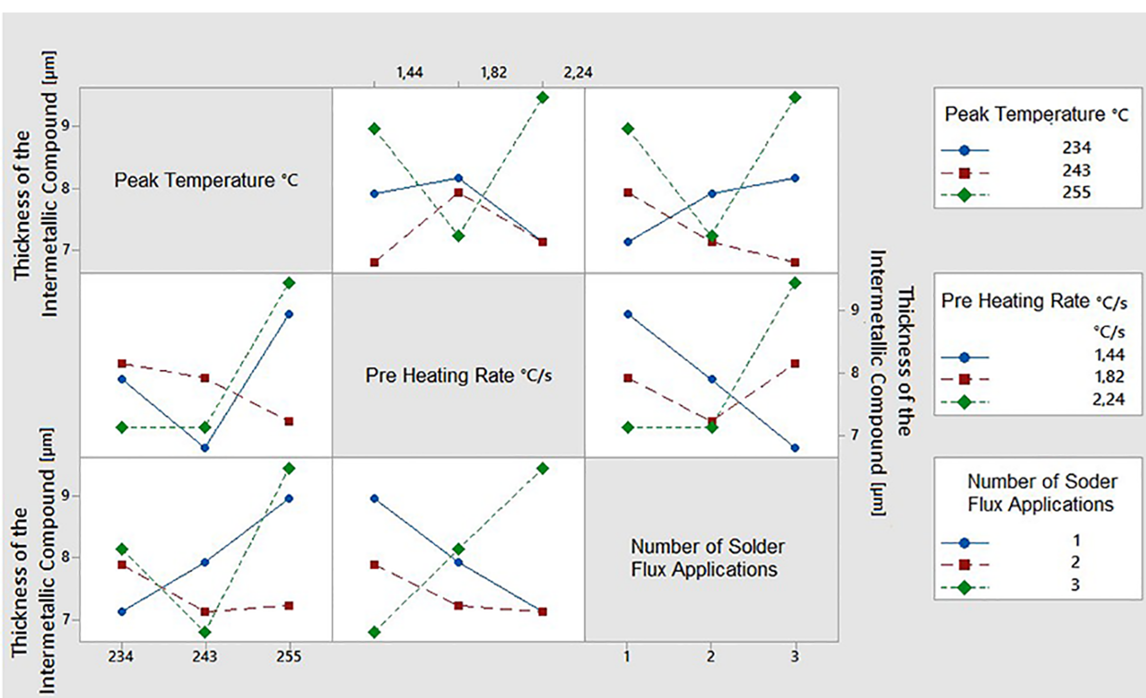

Figure 7. Interactions for the thickness of the intermetallic compound.

4. Conclusions

Shear stress and intermetallic compound thickness of all nine experiments were well distributed, and it was not necessary to exclude any value. All results fit the normal distribution. The ANOVA showed that the means of both shear stress and intermetallic compound thickness of at least two experiments were significantly different.

Considering the factors separately, that is, without the interactions, it was possible to observe that the factor that most significantly influenced shear stress and intermetallic compound thickness was peak temperature, followed by the number of solder flux applications and preheating rate. The levels of each factor that presented the highest shear stress were peak temperature of 255ºC, three applications of solder flux, and preheating rate of 2.24ºC/s. The levels that induced the thinnest layer of intermetallic compound were peak temperature of 243ºC, two applications of solder flux, and preheating rate of 1.82ºC/s.

It was also possible to observe that the interactions between factors affected both shear stress and thickness of intermetallic compound. The combination that induced the highest shear stress was peak temperature of 255ºC, three applications of solder flux, and preheating at 2.24ºC/s. The peak temperature that promoted the generation of the thickest layer of intermetallic compound was 243ºC, together with three applications of solder flux, and preheating rate of 1.44ºC/s.

With peak temperature of 255ºC, three applications of solder flux, and heating rate carried out at 2.34ºC, shear stress was 821.48 gf. The greater the shear stress, the higher the resistance to it. Therefore, this combination of levels of factors used in the experiment induced the greatest resistance to shearing of the solder joint onto the substrate. Considering the peak temperature of 243ºC, three applications of solder flux, and heating rate of 1.44ºC/s, the thickness of the intermetallic compound layer was 6.81 μm. This combination of levels of factors induced the formation of the thinnest layer of intermetallic compound between solder balls and substrate.

5. Acknowledgements

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6. References

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