

Thick Al Ribbon Interconnects: A Feasible Solution for Power Devices Packaging

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Abstract

With the constant drive for smaller, more cost effective power electronic systems offering enhanced performance and reliability, Aluminium (Al) ribbon bonding has become an attractive alternative to the well established thick Al wire bonding. Improved electrical performance and assembly cost reduction are the main expected benefits. Although ribbon bonding is viewed as a drop-in replacement for wire bonding, differences in the details of the joining process are to be expected. The potential effects of those differences on the bond formation and ultimately the bond reliability warrant a more detailed investigation. This work covers a first step, in which we analyze and report the effects of different target bond deformation levels on the strength and reliability of 80 × 8 mil thick Al ribbon bonded with different bond tools. The long-term strength and reliability of these ribbon bonds were assessed under thermal cycling between -60°C to 170°C. Bond shear testing was used to characterize bond strength. Microstructural analysis was performed and the correlation between measured bond shear strength and crack length along the bond interface at increasing numbers of thermal cycles was studied. In summary, both the bond tool type and deformation setting play an important role in determining the thermal cycling reliability of the ribbon bond.

Keywords: Aluminum, ribbon bond, reliability, thermal cycling, bond parameters

1. Introduction

Proliferation of performance and reliability enhancing electronics has fuelled the development of packaging and interconnection technologies to fulfill the requirements of dense I/O and low on-state resistance ($R_{DS(on)}$) [1]. This proliferation is largely driven by the availability of increasingly capable microelectronics, coupled with the burgeoning needs for improved integrated system performance, for example the addition of power control functions. As a consequence, the complexity of package design has tended to increase against a background requirement for high yield, lower cost and shorter manufacturing time.

Flexibility, reliability, and cost in addition to low environmental impact, make large Aluminum

(Al) ultrasonic wire bonding the ideal interconnect choice for complex power electronics applications with high reliability requirements [2, 3]. The properties of Al as an interconnect material also offer a good compromise between performance (electrical resistance) and cost [3]. The spreading resistance and loop resistance can be reduced by increasing the bonded area and increasing the loop cross-section, or shortening the loop length. This can be achieved by having a larger number of stitches on the die and/or a larger number of parallel wires. The overall effect is the desired reduction in $R_{DS(on)}$. However, adding more stitches or wires requires longer processing times. This results in higher manufacturing cost due to a decrease in throughput. Also, there is often limited space to add the necessary number of wires.

Such a solution therefore runs against the competitive market trends for denser packaging, higher current handling capability and lower cost per device.

Large Al ribbon bonding may become an evolutionary extension of the highly effective large Al wire interconnect technology, meeting present and future interconnect needs of the power module market. While it offers the same benefits as large Al wire bonding, it also eliminates, or at least alleviates, some of the limitations of round wire bonding, such as the need for bonding a significant number of parallel wires per device to meet the necessary current or resistance requirements. The number of round Al wires which can be replaced by one rectangular Al ribbon of specific dimensions is shown in Table 1 [4].

The quality of bonding materials and equipment capability are the foremost contributors to the robustness of an interconnect system. Manufacturing technology used in production of large corrosion resistant Al ribbon material has matured recently. During the past two years, the PowerRibbon® technology introduced by Orthodyne Electronics [4, 5] has been put in high volume production for a wide range of applications, from small discrete PQFN packages to large automotive power modules¹.

Large Al Ribbon Size	Equivalent Number of Wires (mil)				
	8	10	12	15	20
40 mil × 4 mil	3.2	2.0	1.4		
40 mil × 6 mil	4.8	3.1	2.1	1.4	
60 mil × 6 mil	7.2	4.6	3.2	2.0	1.1
60 mil × 8 mil	9.5	6.1	4.2	2.7	1.5
80 mil × 8 mil	12.7	8.1	5.7	3.6	2.0
80mil × 12mil	19.1	12.2	8.5	5.4	3.1

Table 1: Equivalent number of Al wires that can be replaced with a single Al ribbon of respective size.

Although ribbon bonding is viewed as a drop-in replacement for wire bonding, differences in the details of the joining process are to be expected, which may potentially affect the bond formation and ultimately a bond's long-term reliability. In this work, we report the effects of different target bond deformation levels on the strength, quality and reliability of 80×8 mil thick Al ribbon bonded with different bond tools. The results of these initial studies will be used to further develop, improve and optimize the PowerRibbon® bonding technology.

¹ PowerRibbon® is a registered trademark of Orthodyne Electronics Corporation, Irvine, California.

2. Experimental Consideration

(A) Ultrasonic Bonding of Large Al Ribbon (PowerRibbon® Bonding)

The Al ribbon bonds evaluated in this study were made using Orthodyne Electronics' PowerRibbon® technology on the 3600R large ribbon bonder. This technology is designed to work in existing Al wire bonding applications, combining the flexibility and robustness of the large Al wire bonding process with a higher productivity and improved product performance. The 3600R equipment is capable of bonding ribbons with size up to 80×12 mil (2×0.3 mm). The bonding times are comparable to the ones used for round wires with diameter approximately twice the ribbon thickness.

A dedicated work holder was not available to secure the substrate during bonding. It was observed that the exact clamping of the substrate had an influence on the bond behavior. A contribution of this not perfect fixture to the variation in bond results thus cannot be excluded.

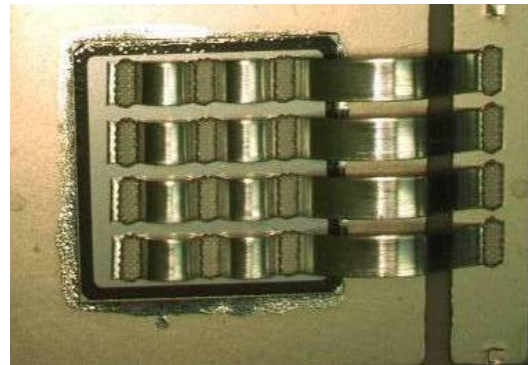


Figure 1: Four ribbons of size 80×8 mil ultrasonically bonded on a silicon die with $5\mu\text{m}$ thick Al top metallization.

A total of four ribbons are bonded onto the $12\text{mm} \times 12\text{mm}$ silicon dice with a $5\mu\text{m}$ thick Al top metallization. The dice are mounted onto an aluminum nitride ceramic substrate, as shown in Figure 1. The layout allows to fit a large interconnect cross-section with a minimum number of ribbons, each with three stitches, into the available bonding space. Control of the ribbon placement was identified as critical parameter for the 3 stitches configuration. A configuration with multiple stitches is closer to a real application. Since the stitch bond also has a shorter loop in front of the bond, the stitch bond behavior may be different from the first bond. The increased number of bonds allows more measurement data to be collected for a given number of test dice. The material properties of Al ribbon used in this

work are kept comparable to the soft, annealed and corrosion resistant conventional round 99.99% pure Al wire.

Bond tools with cross-type pattern and specific foot length are used for bonding the large Al ribbons. In this study, four different bond tools were employed. Deformation patterns of the ribbon bonds created by each bond tool, namely 8008, 8010, Sk1 and Sk2, are depicted in Figure 2. An interlacing web deformation is created and expected to facilitate Al diffusion at the bond interface [4], forming a more robust bond. Tools 8008 and 8010 are the standard bond tools for 8mil and 10mil thick ribbon, respectively. The tool 8010 has longer 'teeth' than the 8008 tool. The Sk1 tool has a narrower foot, creating a bond with square area, which is longer but narrower than those of the 'standard tools'. The Sk2 tool is similar to the standard tools but with a different foot structure.

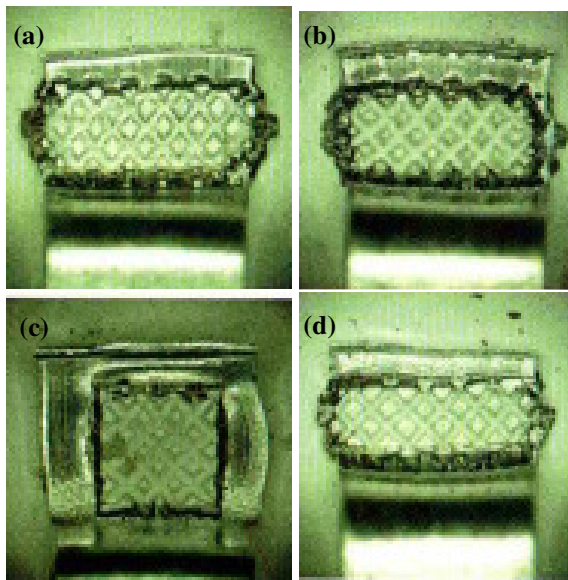


Figure 2: Ribbon bond deformation patterns created by four different bond tools: (a) 8008, (b) 8010, (c) Sk1 and (d) Sk2.

The ribbon bonding process is performed with different target bond deformation levels using respective bond parameters. The deformation levels, Low and High, were chosen to be sufficiently below (Low) and above (High) what is considered an optimum bond deformation. This was done in order to create results that are significantly different with respect to the characteristics of interest, the long-term strength and reliability of the joint. That said, it cannot be excluded that especially the bonds with the High deformation setting are rather over-bonded, and should therefore not be viewed as representative for

the optimum bonds with regards to visual appearance.

(B) Testing and Cross-Sectional Analysis of Large Al Ribbon Bonds

The ribbon bonded devices were subjected to repetitive passive thermal cycling in air from -60 to 170 °C, with 30 minutes holding time and an hour for one complete cycle. The bond degradation behavior was characterized by the shear force measurements at regular intervals. Shear direction was along the ribbon. A shorter work holder with a wider base is used to resist the bending moment force induced as a result of high shear force levels required on the large ribbon bonds. The shear testing module is attached onto a thick Al carrier block with a wax commonly used in silicon wafer processing, in order to prevent the samples from moving relative to the shear bit during testing [6].

A number of ribbon bonds were prepared for cross-sectional analysis. The cross-section devices were polished, anodized and examined under an optical microscope with polarized light to reveal the grain structures in the ribbon, bonding pad and bond interface. The anodizing solution used is known as Barker's Reagent which is made up of 5% by volume Fluoroboric acid in water.

3. Results

(A) Shear Strength of Al Ribbon Bonds After Bonding

Prior to passive thermal cycling from -60°C to +170°C, the initial shear strength of ribbon bonds was assessed by means of a destructive shear test. A comparison of the mean shear forces for Low and High bond deformation settings as a function of bond tool type is depicted in Figure 3. The average force required to shear off a ribbon bond is found to vary with the bond deformation level, and to depend on the bond tool type. However, the average shear forces for all configurations (bond tool, deformation level) are above 10 kgf and can be considered high for a 80 x 8 mil ribbon [6]. The shear data unambiguously indicate that good bonding has been achieved for all bond tools and target bond deformation settings investigated.

For round wire bonds, a higher shear force is expected for greater bond deformation [7]. This is because the higher bond deformation creates a larger bonded area. However, this does not apply to ribbon bonds, where the deformation level is expected to primarily affect the strength of the joint interface.

However the measured shear force will depend on the bond geometry and bond thickness [8].

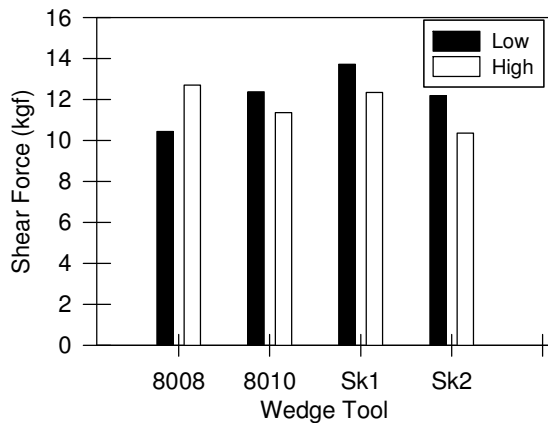


Figure 3: Average initial shear strength of ribbon bonds joined at the Low and High deformation settings using 4 different bond tools.

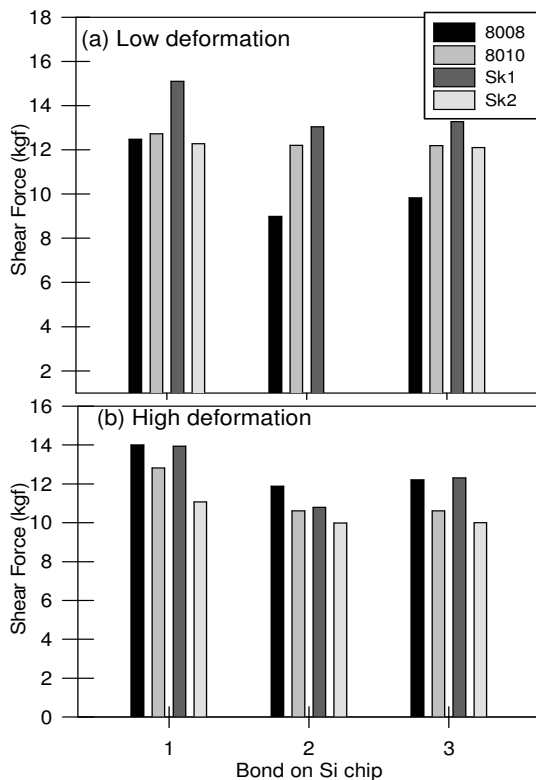


Figure 4: Average shear strength for first, second and third bonds on the Si dice for different target deformation levels.

Only tool 8008 shows a higher average shear force for the High deformation level, according to the data shown in Figure 3. This indicates that the Low deformation setting did not create a sufficiently

strong bond interface. The lower measured average shear forces for the High deformation settings for the other three bond tools (Figure 3) are believed to be caused by the reduced bond thickness, which is lower for bonds with higher deformation, and also certain measurement variations. As described in [6], shearing fairly thin bonds at such high loads is a difficult process.

Figure 4 summarizes the average shear force for the first, second and third (last) ribbon bond on the Si dice for the two bond deformation levels. The stitches were bonded about 3mm apart. For devices bonded with tools 8008 and Sk1, the first stitch was significantly stronger than the subsequent stitches at both Low and High bond deformation levels. In contrast, the individual mean shear forces of ribbons joined using tool 8010 and Sk2 at the Low bond deformation level were indistinguishable for the three stitch bonds on the dice. However, increased bond deformation level gives rise to lower shear forces for the 2nd and the last stitches when compared to the 1st stitch bonded with tool 8010 and Sk2.

Due to the loop in front of the bond, a stitch bond can be joined less efficiently than the first bond. This is depending on the length and height of the ribbon loop, i.e. its stiffness [9], as the loop may slightly dampen the tool tip vibration. A bond tool with longer teeth, for example the 8010 tool, is expected to be less affected. This may explain why the 8010 tool shows a similar shear force for the stitch bonds as for the first bond, for the same bond parameters.

The first bond can be sheared along the ribbon from the tail side, without further preparation. In contrast, the stitch bond can only be sheared the same way after properly removing the loop. Therefore, a larger measurement variation must be expected for the stitch bonds.

(B) Thermal Cycling Behavior of Al Ribbon Bonds

Figure 5 gives a general overview for the bond strength behavior of the Al ribbon bonds as a function of the number of thermal cycles. The decrease in the mean shear force with an increasing number of thermal cycles can be explained by a reduction in bonded area. This is due to the cracking induced during the thermal cycling. Figure 3 indicates a very small decrease in the measured shear force for Low and High deformation bonds up to 1000 thermal cycles between -60°C and +170°C. The bonds with High deformation continue to show a small additional decrease in strength up to 2000 thermal cycles, while the data indicate a more drastic decrease for the bonds with Low deformation.

Bonds with the High deformation setting show less than 20% decrease in strength after 2000 thermal cycles. Conversely, bonds with Low deformation still retain more than 50% of their initial strength. The longevity of these bonds is exceptional, as the test conditions with large temperature swing of 230°C appear to be much more severe than, for example, the test conditions for automotive applications (-40°C and +125°C). However, recent experimental results show that the degradation behaviour of the bonds may depend on the thermal cycling conditions [10]. That study showed that bonds subjected to testing with higher maximum cycling temperature actually degrade less rapidly. This possibly is due to the annealing effects, which occur in the bonding materials during the high-temperature phase of the thermal cycle [10].

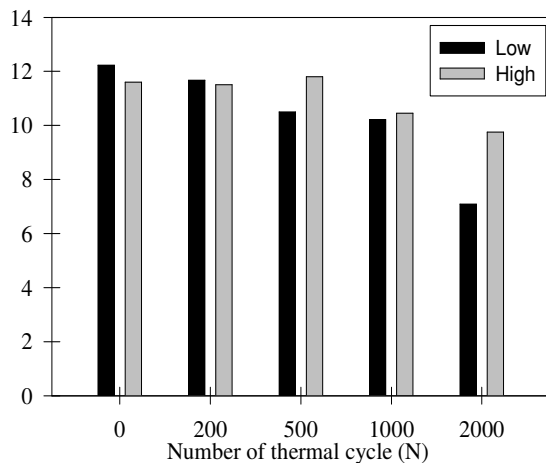


Figure 5: Measured mean shear forces of Al ribbon bonds, for the Low and High deformation levels, as a function of the number of thermal cycles.

Given that the shear strength of such ribbon bonds is sensitive to the length of crack progression [11], it can be assumed that the bond degradation rate depends strongly on the crack propagation rate at the bond interface. This may indicate that the crack propagation across the welded area is more suppressed at the High bond deformation level, leading to improved reliability of the ribbon bonds for all bond tools.

Figure 6 compares the measured mean shear forces for the individual bond tools and bond deformation levels. The bonds of all configurations degraded in a similar way as shown in Figure 5, irrespective of bond tool type.

The slowest bond degradation rate was found for ribbons bonded at the High deformation setting using the tool 8010. This implies that the

integrity of the bond was improved by using a bonding tool with longer 'teeth' and the High deformation level, and consequently, the bonds were less susceptible cracking.

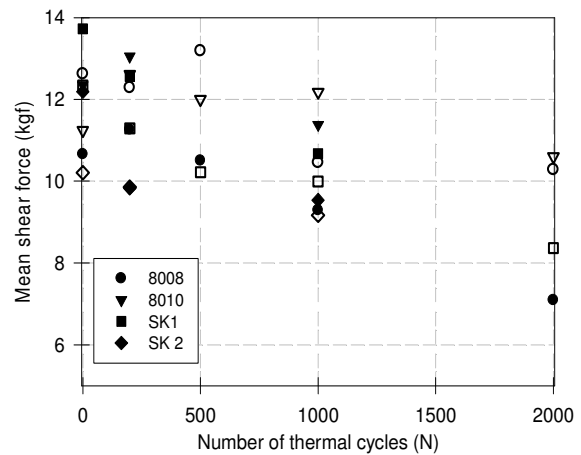


Figure 6: Mean shear force for ribbons bonded with different bond tool types at the Low (filled symbols) and High (unfilled symbols) bond deformation levels.

4. Discussions

(A) Ribbon Bond Interfacial Micro-structural Analysis

Cross-sections of ribbons joined using various bond tool types and bond deformation levels were characterized and are shown in Figure 7. The bonds formed using tool 8008, are less sensitive to the bond deformation levels. Conversely, ribbons bonded at the High deformation setting exhibited thinning at the heel and appeared to be over-compressed using tool 8010, Sk1 and Sk2. This observation agrees well with the initial shear strength data (refer to Figures 3 and 4), suggesting that the High bond deformation setting is more than the optimum for these three bond tools.

Differences in the microstructures of the ribbon bond cross-sections were revealed after anodizing in the Barker's Reagent. The grain structures and number of bonded areas were closely related to the bond deformation setting and bond tool types. Fiber texture consisting of elongated and non-recrystallized grains were found in most of the Low deformation bonds.

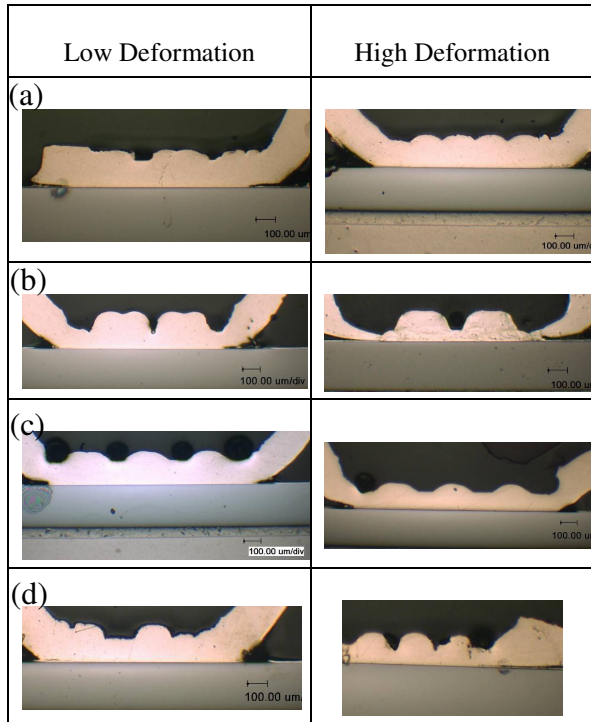


Figure 7: Cross-sectional images of bonds for all four different bond tools: (a) 8008, (b) 8010, (c) Sk1 and (d) Sk2, for the Low and High bond deformation levels, respectively.

An example of a bond joined using tool Sk2 at Low deformation setting is shown in Figure 8(a), which is also found to have the highest number of small un-bonded regions at the bonding interface prior to thermal cycling. In contrast, there were fewer un-bonded regions at the bonding interface for highly deformed bonds (Figure 8(b)). This observation suggests that a high degree of bond deformation creates a more homogenous and stronger metallurgical joint.

Improved bond adhesion using a higher bond deformation setting has been shown to have significantly reduced the number of un-bonded areas, so that bonds are more resistant to crack propagation when subjected to repetitive thermal loading. This result agrees well with the literature [7].

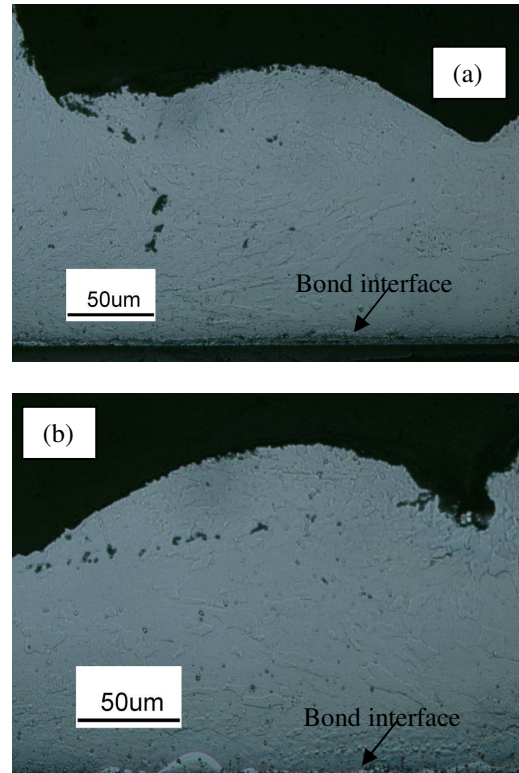


Figure 8: Anodized images of bonds with (a) tool Sk2 with the Low deformation setting and (b) tool 8010 with the High deformation setting.

(B) Cracking Mechanism in Al Ribbon Bonds

Figure 9(a) shows the cross-sections of a bond formed at Low bond deformation setting using tool 8008 prior to thermal cycling. A gap is seen under the bond heel, likely as a result of the mechanical deformation and ribbon flexing when forming the ribbon loop. Due to the mismatch of thermal expansion coefficients between the Al and Si, a significant thermo-mechanical stress is induced at the bond interface, especially at the bond heel. A pre-existing gap with the shape shown in Figure 8(a) creates a stress concentration point, which is likely to enable or accelerate the formation of a crack induced during thermal cycling, and consequently decreases the bond's lifetime.

Figure 9(b) shows a bond created with the same tool and deformation level after 500 thermal cycles. A crack has formed at the heel and has propagated from the bond heel towards the bond's center. This bond shows a different gap under the heel, implying that this gap can be affected, and likely eliminated by proper process settings.

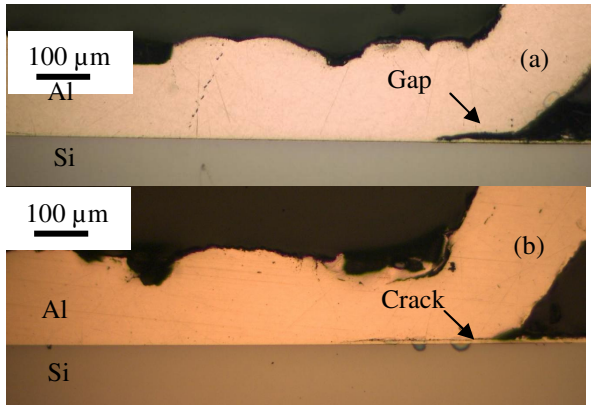


Figure 9: Optical micrographs showing the crack location for ribbon bonds using tool 8008 with Low bond deformation level, after (a) $N = 0$ and (b) $N = 500$ thermal cycles.

Figure 10 shows the average crack lengths versus the number of thermal cycles. The data given for $N = 0$ thermal cycles represent the length of the gap under the heel, as discussed above. Obviously, that gap is of significant length compared to the crack propagation during subsequent thermal cycling. Eliminating that gap may therefore lead to a significant increase in the lifetime of such bonds.

Longer gaps at $N = 0$ thermal cycles were found in the bonds formed using tool 8010 with High deformation setting, which also corresponds to the lowest initial bond shear strength. However, after 500 thermal cycles, cracks were found to advance more rapidly in bonds with High deformation setting using the tool Sk2. This observation is in good agreement with the results for the measured bond shear force, indicating that crack propagation rate was suppressed in the absence of a significant number of un-bonded regions for ribbon bonds formed using higher bond deformation, i.e. using tool 8010 at high bond deformation setting.

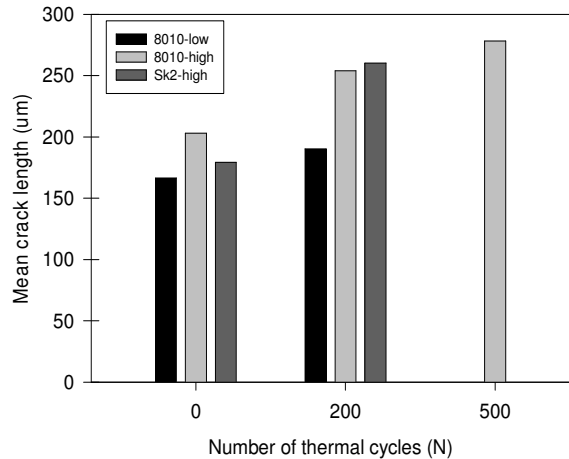


Figure 10: Mean gap ($N = 0$) and crack ($N > 0$) length as a function of the number of thermal cycles N , for ribbon bonds using tool 8010 and Sk2.

4. Conclusion

A study of the performance and thermal cycling behavior of ultrasonically bonded large Al ribbons has been performed. Both the bond tool type and bond deformation setting play an important role in determining the long-term strength and reliability of such bonds. Good ribbon bonding was achieved for all possible combinations of bond tool and bonding parameters, giving rise to high initial bond shear strength within the expected range for an 80×8 mil ribbon bond.

When subjected to repetitive thermal cycling, the average force required to shear off a ribbon bond was found to decrease with increasing number of thermal cycles due to the reduction of bonded area, a consequence of crack propagation from the bond heels to the centre of the bond.

Ribbons bonded using tool 8010 with high deformation level had the lowest initial shear strength, they were found to degrade at the slowest rate compared to those bonded using tool 8008, Sk1 and Sk2. This may imply that the crack propagation rate at the bond interface and bond shear force are sensitive to the size of the welded area on a microscopic level.

Micro-structural studies of these specimens have shown that the higher endurance of the ribbon bond was mainly due to the improved bond adhesion by increasing bond deformation. A remarkable drop in the number of un-bonded regions at the bonding interface can be achieved by having a good

combination of high deformation setting and bond tool type, i.e. with deeper teeth.

Given the large temperature swing between -60°C and +170°C, it is very impressive to observe average bond strength degradation of less than 20% and 50% for the High and Low bond deformation settings, respectively, after 2000 thermal cycles.

However, with the present tools, for the High deformation settings, the heels of the ribbon bonds were considerably weakened and metallurgically overworked. Although none of the samples showed bond heel failure, the long-term effect of this damage on the overall interconnect reliability is yet unknown. Since large ribbon bonding is still a relatively new technique, there exists ample need, but also potential for improvement. The next step will therefore focus on the bond tool design and process aspects to retain the observed level of bond strength and reliability, while minimizing damage to the bond heels due to bond over-deformation.

In summary, large Al ribbon bonding can be considered a feasible drop-in replacement for thick Al wire bonding, with very good reliability behavior, once its bonding process is fully optimized.

5. References

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