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Wear optimized consumables for copper wire bonding in industrial mass production

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Abstract

Copper wire as a bonding material for the top side connection of power semiconductors is highly desired. One current drawback in heavy copper wire bonding is the relatively low lifetime of the consumables. The bonding tool wear mechanisms and the corresponding factors are investigated in this contribution. Different approaches to reduce wear are tested in long-term bonding tests. Optimized bonding parameters and special tool material are two of these. Incorporating both, an immense improvement in tool lifetime of a factor of more than 15 was achieved. Wear and lifetime of cutter and wire guide are also examined. Additionally, the impact of bonding tool wear on different aspects of bond quality is addressed. It is also shown how wear can be monitored by machine process data recording and how a derived signal correlates to the actual wear status. These major advances in heavy copper wire bonding now make it a robust, reliable and efficient interconnection technology.

1 Introduction

In the last few years new technologies for connecting power semiconductor devices have been developed to fulfill the increasing demands of high performance and high reliability applications, like the growing markets of renewable energy and electric vehicles. Major trends are higher power density and higher junction temperatures. Besides advanced die attach techniques like sintering, the top side connection also has to be improved. Aluminium cannot be the material of choice anymore, due to its limited electrical conductivity and temperature stability. Instead copper wire as a bonding material is highly desired, because of the superior material properties. The electrical and thermal conductivity, as well as the mechanical stability of copper interconnections, are significantly higher than those made with aluminium. Additionally, copper wire bonded on copper-metalized dies shows reduced thermo-mechanical mismatch and thus increases the lifetime and reliability of the topside die interconnection. [1], [2]

Products with copper wire technology are already available (Figure 1) and increasingly more will be launched in the near future.

2 Copper Wire Bonding Advantages and Challenges

The major drawback in heavy copper wire bonding is the low lifetime of the consumables, especially bonding tools and cutters. Compared to aluminium, Young's Modulus and yield strength of copper are significantly higher. Because of this, bonding force and ultrasonic power are about 2 to 3 times as high compared to standard aluminium bonding. In combination with the hardness and abrasive properties of the copper wire, this significantly reduces the lifetime of the consumables.

Due to the reduced lifetime of the consumables and the higher price of copper wire per meter, the process costs are currently higher compared to aluminium. This still prevents the use of copper in place of aluminium in mass production. In addition, the products and the semiconductors have to be designed for the use of copper wire. Aluminium as a top side metal on dies or leadframes does not allow copper wire bonding.

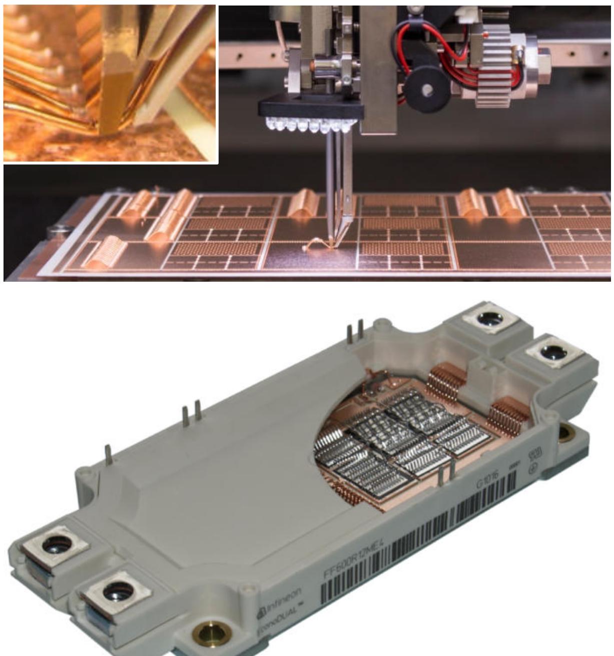

Figure 1 20 mil Copper wire bonding (top) and power semiconductor module with copper wires (Infineon Technologies, bottom)

State-of-the-art aluminium wire bonding processes have a change interval for the bonding tool of about 100'000 touchdowns (TDs). Bonding tools can be cleaned by removing the material build-up occurring in the process, and reused several times up to a total of about 1 million TDs. The same application with copper wire has a typical bonding tool change interval of not more than 30'000 TDs. With copper wire there is no material build-up which could be removed by cleaning, but the bonding

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tool is worn out. The reduced change interval results in increased machine downtime and more operator support. Together with the increased bonding tool costs this results in higher cost per unit which makes copper wire bonding more cost intensive.

From this state of the art, we can set two targets for tool and machine suppliers. First, to increase the lifetime of copper bonding tools by changing material, design and bonding process parameters and second, to implement a non-destructive quality sensor to ensure the required interconnection quality and to determine the actual wear status of the bonding tool.

3 Tool Lifetime Investigation

3.1 Experimental setup

For the lifetime investigations an experimental setup with 'typical' parameters and components for 500 µm (20 mil) copper wire bonding was chosen. The wire used is *PowerCu* from Heraeus. Because of the immense amount of bonds required, ordinary copper plates with a clean and smooth surface were used for bonding. The experiments were done on a Hesse BJ939 wire bonder with a back-cut copper-bondhead, being able to supply bonding forces up to 4200 cN and ultrasonic power up to 120 watts.

To accelerate the lifetime investigations, single bonds without looping were made (see Figure 2 and Figure 3).

3.2 Tool wear mechanisms

Figure 2 shows bonds made with a new tungsten carbide tool. This tool acts as the reference for all following investigations. Figure 2 (a) shows the top view on the bond foot with the two contact areas of the tool V-groove, which are roughly elliptical with a smooth mat surface. There is no strong material yielding in the bond center. The width of the bond foot is quite small compared to aluminium bonding, only around 120% of the wire diameter.

With this reference setup, the shape and the surfaces of the tool tip and the bond foot change significantly during repeated bonding. The contact surfaces are worn out (Figure 2 (c)). There is no material build-up on the tool as with aluminium bonding, but rather excessive wear at the contacting surfaces of the V-groove.

The mechanisms causing this wear are mainly abrasion and plastic deformation. This is reported in detail in [3] and [4]. Additionally, breaking of surface material and the recurrent deposition of small particles of copper oxide is reported there.

It is believed the root cause of all these wear mechanisms is locally high mechanical pressure in the wire/tool contact area in combination with the material parameters of copper. It is also believed that relative motion between the tool and the copper wire is a main cause of wear. At the end of the bonding process, the lower side of the wire is already connected to the substrate while the tool still vibrates. The relative motion between tool and quasi-fixed substrate can be compensated by elastic deformation of the wire and by relative motion between tool and wire ('micro-slip'). Because of the higher Young's Modulus of copper compared to aluminium, there is less elastic deformation and thus increased micro-slip becomes an issue. The shiny and very smooth surfaces of the worn tool tip depicted in Figure 1 (c) support this hypothesis. Additional indicators for this are also reported in [3] and [4].

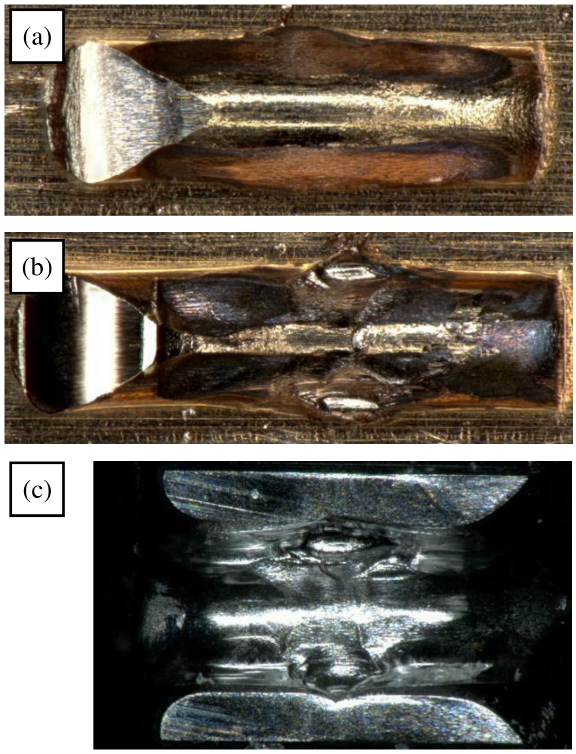

Figure 2 Bond foot with reference parameters for a new reference tool (a), after 25k bonds (b) and corresponding tool tip topography (c)

3.3 Impact of tool wear on bond quality

A main question concerning tool wear is to what extent bond quality is affected. Generally the impact of tool wear on bond quality depends on the specific process, the bonding tool used and especially on the interpretation of 'quality'. In this context bond quality is understood not only as constant mechanical bond strength, also optical appearance of the bond foot and process data recorded by the machine are taken into account. These three branches can be influenced by wear in different ways and to different degrees.

As can be seen in Figures 2 and 3, the surface topology on the top side of the bond foot is changing as the tool wears. This is a continuous process. Shiny areas in the contact area between tool and wire can be seen both at the bond foot and at the tool tip, indicating micro-slip. Additionally, when the wear has reached a certain level, tool contact with the substrate occurs during bonding, see Figure 3 (c) top right corner. This inhibits further bond deformation and reduces the effective normal force acting on the bond. If these tool touchdowns occur more frequently and with stronger impact this will reduce the bond quality and the shear values in the same degree (see chapter 3.5). This is the ultimate signal for End-of-Life (EoL) of the bonding tool.

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But until this stadium the observed tool wear does not directly correlate with the bond strength and the shear values. The shear values stay constant for many bonds (see Table 1), despite the ongoing wear. Investigations in [6] of the shear surfaces (surfaces after shear test) have shown that even though the contact surfaces at the tool tip are strongly worn after 100k bonds, the effective contact area between substrate and wire is almost the same as with a new tool. Obviously, the normal forces acting on the wire as well as the ultrasonic coupling between tool and wire are still sufficient to form a stable interconnection at this level of wear. Nevertheless, the process will change with further increasing wear and to some degree, bond quality will degrade. It should be pointed out that while the principal wear mechanisms are the same for bonding on Direct Bonded Copper (DBC) substrates, as already observed in [3], [4], their specific extent can be different on DBC than it is on the investigated copper plates.

3.4 Impact of bonding parameters on wear

The bonding parameters do not only have a big influence on the bonding itself, they also have a strong impact on tool wear. The most important parameters are the ultrasonic amplitude or power, the (normal) bonding force and the initial touchdown force [5]. Generally ultrasonic amplitude and bonding force are varied linearly in some intervals during bonding. This gives a great multitude of possible parameter sets and therefore bonding processes.

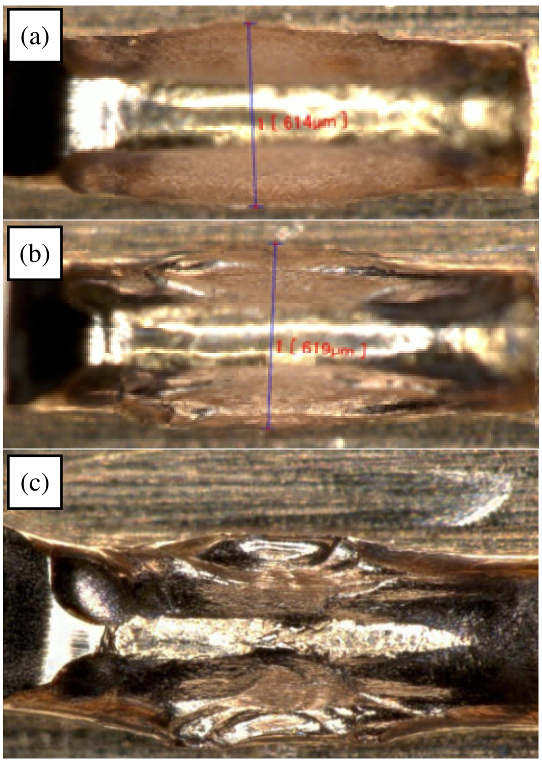

Figure 3 Bond foot with optimized parameters and new reference tool (a), after 25k bonds (b) and 100k bonds (c)

As shown in chapter 3.2, with the reference bonding tool and the reference bonding parameters the wear of the tool tip progresses quite fast. These parameters were developed for maximal bonding strength with a high safety margin, tool wear was not in the focus. It was possible to find an alternative set of parameters with equivalent bonding performance, but with much less tool wear. The main reason for this was a reduced bonding time of less than 200 ms instead of more than 300 ms in the reference parameter set.

Despite the shorter bonding time, this wear-optimized parameter set showed the same optical and mechanical quality as the reference parameter sets. Figure 3 depicts the quality and wear status of the bond foot over time. The corresponding shear values are part of Table 1 (Tool A). Comparing the contact surfaces of the bond feet in Figure 2 (a) and Figure 3 (a) also reveals the reduced micro-slip with the optimized parameters as the main driver for tool wear. While the reference process shows quite pronounced smooth and shiny surfaces in the outer contact area, in case of the wear-optimized process the surfaces look more mat and uniform. Even after 25k bonds the contact surfaces still show not much degrading, at least in the centre of the contact area. After 100k bonds also with the optimized parameters increased micro-slip apparently occurs. Additionally, increased tool touchdowns indicate tool-EoL in this state of wear. But it can be pointed out that with optimized bonding parameters the tool lifetime can be raised by a factor of 4 without loss of bond quality. This is a big improvement in copper wire bonding.

3.5 Impact of tool material on wear

The most important factor in tool wear and tool lifetime is of course the tool tip material itself. If the material cannot withstand the extreme high static and dynamic stresses and strains in heavy copper wire bonding, tool lifetime will not reach the benchmark level of aluminium bonding (see chapter 2).

Since decades the standard tool material in heavy (aluminium) wire bonding is tungsten carbide. But also advanced materials for better grip and increased lifetime are available. Primarily these are so called cermet materials. Cermet material is a composite of a ceramic base material in a metallic matrix. Bonding tests with such a cermet tipped tool (Tool B) have also been conducted, but no significant improvement in lifetime was found. In [3] it is reported that for heavy copper wire bonding the wear mechanisms are basically the same as for reference tungsten carbide material, but occur in a different extent.

In lifetime tests a tool with a special wear resistant tip material (Tool C) showed superior performance and sustainability. These tests were planned to compare the main tool materials under equal conditions to yield a real benchmark. Test were repeated – where possible even with material from different tool suppliers – to get reliable results. For all tests the optimized parameter set introduced in chapter 3.4 was used. Additionally the conditions specified in chapter 3.1 have been applied.

All relevant information and measures for the examination of the wear progression have been collected and evaluated.

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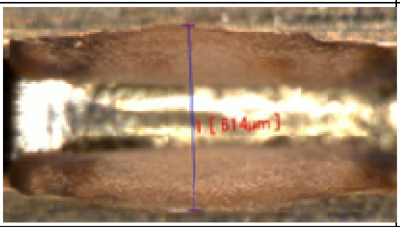
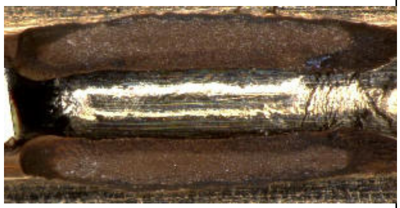
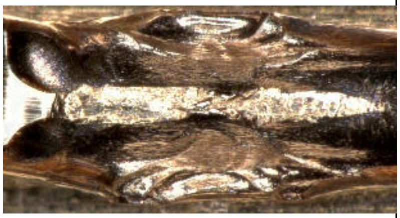
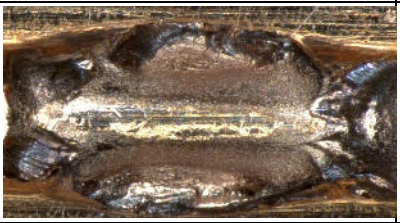
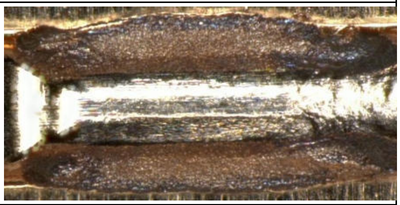
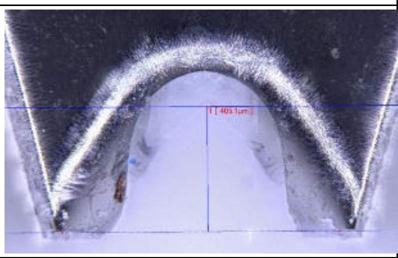
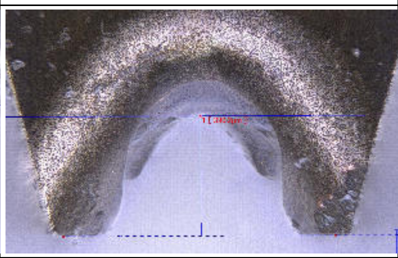
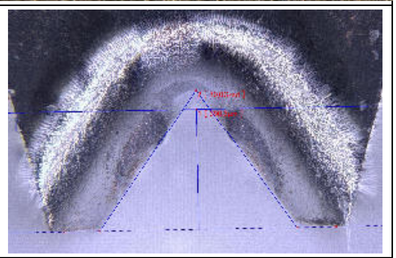
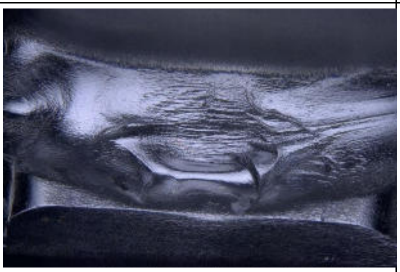
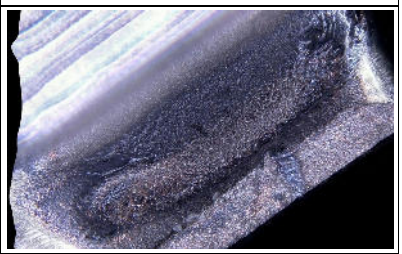
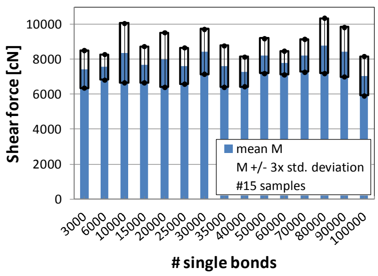
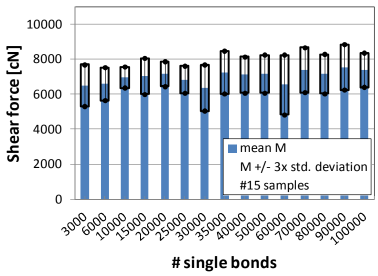
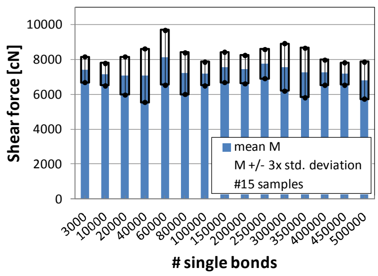
	Tool A (Tungsten Carbide)	**Tool B (Cermet)**	**Tool C (Special Tip Material)**
Bond foot **New tool**			
Bond foot **100k bonds**			
Bond foot **500k bonds**	–	–	
Tool back side **100k bonds**			
Tool flank **100k bonds**			
Tool flank **500k bonds**	–	–	
Shear values			

Table 1 Comparison of tungsten carbide tool, cermet tipped tool and special wear resistant tool. Note the extended amount of bonds for tool C of up to 500’000 (different intervals for shear values)

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Microscope pictures of the bond foot and the tool tip contact area have been made in an interval of at least 10k bonds. Corresponding shear test values have also been recorded (Table 1) as well as continuous machine data from the quality monitoring system (see chapter 4).

The main results are depicted in Table 1. As already stated in chapter 3.4 the tungsten carbide tool (Tool A) reached its EoL at 100k bonds. The shear values show a drop from stable 8000 cN (gf) to 7000 cN at 100k bonds. The wear has significantly changed the topography of the bond foot. The flanks are strongly deformed with wavy structures. The bond foot crest is smaller compared to the initial state. This is an indication that material has been worn-out, so that copper wire material can flow deeper into the V-groove during bonding. The back side view also shows deep carving of the wire into the tool flank. This wear out causes tool touchdowns during bonding starting at 90k bonds. Shiny surface areas on the bond foot but especially at the tool flanks also indicate micro-slip and a loss of grip.

The course of wear for the cermet tool (Tool B) is very similar to the tungsten carbide tool. First tool touchdowns were noticed at 95k bonds. The shear values stay constant around 7000 cN. But the optical appearance of bond foot, tool flanks and tool back side together with the appearance of tool touchdowns and the indication of the machine data (wear monitor in chapter 4.2) attest that this cermet tool is very close to its EoL after 100k bonds.

Tool C shows a totally different performance. It was driven to half a million bonds and still showed very little wear and very good bonding results. The appearance of the bond foot almost stayed constant with constantly formed mat contact surfaces and a constant wide crest. No carving in the back side view is visible. The tool flanks only show a minor wear at the contact area. In comparison with the tungsten carbide and the cermet tool the surface seems quite rough with a coarse texture. It can be assumed that there is less micro-slip which additionally prevents wear. The shear values did not degrade noticeable till 500.000 bonds, showing values of about 7000 cN. No tool touchdowns were observed and the machine data monitored only small deviations from initial state. The test was stopped at half a million bonds because of lack of time and material, but it was repeated with an identical tool later and identical results were achieved till 500k. It can be assumed that many more bonds can be made with this tool untill its EoL will be reached. If 1 million bonds will be reached, this would be the same amount as can be reached currently in aluminium bonding when tools are cleaned several times.

This result is really a breakthrough for heavy copper wire bonding. If the benchmark lifetime is compared to the initial lifetime a multiplication factor of more than 15 has been proven and even more is expected.

3.6 Impact of tool tip geometry on wear

To suppress or at least reduce the relative motion between bonding tool and wire, a modified tool tip geometry was introduced in [7] and investigated in [3], [4]. Slightly reduced wear and a reduced process fluctuation were reported, but a significant reduction of the micro-slip could not be proven. This is in agreement with results of bonding experiments done within this study. Compared to the reference tool, an increased lifetime of about 30% was observed. Further studies on geometry optimization are ongoing and will be reported in the future.

4 Monitoring Tool Wear

To monitor the bonding tool wear and indicate the need for a tool change, appropriate machine data has to be collected and processed and a 'wear monitor' signal has to be derived.

4.1 Machine data processing

Modern wire bonding machines are able to monitor a multitude of different process signals in real time such as ultrasonic current, vertical wire deformation and resonant frequency during bonding. In this study the wire bonder was equipped with a process integrated quality control system (PiQC), providing an additional mechanical ultrasonic vibration signal as well as a derived friction-related signal [8], [9].

The bonding tool wear affects the different physical machine signals to a different extent. The vertical wire deformation was found to be especially sensitive to bonding tool wear. As discussed in chapter 3.2, the geometry of the bonding tool contact area changes due to the ongoing wear. This affects the wire deformation signal.

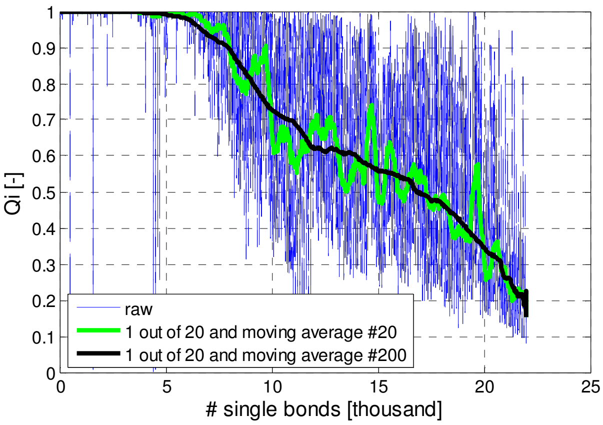

Figure 4 Wire deformation quality index and derived wear monitor signal

Figure 4 shows the quality index related to wire deformation supplied by the PiQC system over time. The bond process is a deterministic and stable process. But as any real world system – and thus all process signals – it is subject to natural fluctuations to some extent. This is taken into account by the PiQC system which returns a quality index of 1 as long as the fluctuation stay within a certain limit [9]. If the mean values are subject to a steady drift, caused for example by wear, these natural fluctuations must be smoothed or filtered in order to derive a meaningful 'wear' signal. Figure 4 shows two filter approaches with 1:20 resampling and moving average filters of width 20 and 200, respectively. The latter combination was found to be a good wear monitor signal.

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The sensitivity of the overall quality index is typically lower than the quality index of the wire deformation, because the other signals included in the overall index are influenced by wear in minor degree. In cases the wire deformation is affected by other process deviations in the sense of 'disturbances', the overall quality index could react more 'robust' to tool wear and could be used as an alternative.

4.2 Online detection of tool end-of-life

This approach was tested for different bonding tool and parameter set-ups. Figure 5 shows the course of the calculated wear monitor signals for the three bonding tools introduced in chapter 3.

The reference tool A was tested with reference parameters and with the optimized parameters. This data corresponds to the tests described in chapter 3.2 and 3.4 (Figure 2 and 3). Tool A with reference parameters showed a very quick decrease of the wear signal. After less than 25k bonds the tool is strongly worn, as can be seen in Figure 2. An identical tool reached 4 times this number of bonds when optimized parameters are used. This is seen in Figure 3. Tool B with the cermet tip showed no significant improvement in lifetime, see Table 1. This also correlates with the results shown in Figure 5. The wear monitor signal for tool C stayed constant till 100k bond and only showed minor degradation till 500k bonds (not depicted in Figure 5).

For other bonding tool types with different foot shapes the results and the sensitivity were different. The adjustment of cutter and wire guide can also have an influence on this signal. A change in the wire position within the V-groove caused by improper cutting or misalignment of the wire guide can cause changes in the bonding process and especially in the wire deformation signal.

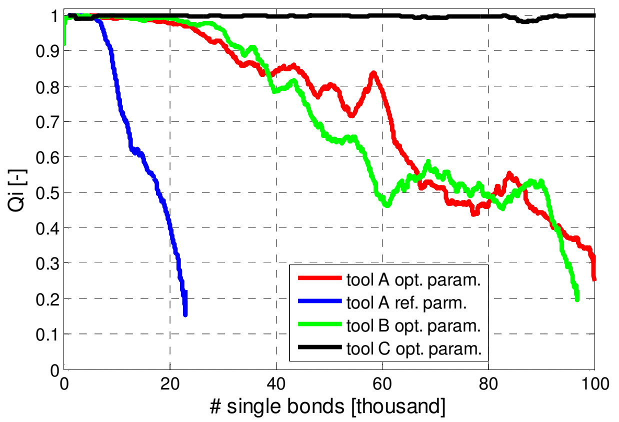

Figure 5 Wear monitor signal up to 100k bonds

If the wear monitor signal steadily falls under a user defined threshold, a critical tool wear could be detected and a bonding tool change can be triggered accordingly. A bonding tool EoL-threshold (End-of-Life) for the wear monitor signal is only valid for one specific set-up.

Not yet taken into account are other 'disturbances' of the process, like changes in the bonding devices, the wire, or other environmental events which could influence the bonding process. This will be part of future work.

5 Cutter and Wire Guide Lifetime

Besides the bonding tool, the cutter and the wire guide are the other consumables relevant for copper wire bonding. Copper wire bonding will be competitive and cost-effective only if all these consumable show a reasonable lifetime.

In the beginning of copper wire bonding standard cutters for aluminium bonding were used. These were made of hardened steel. However, these could not sustain for long because of the hard copper wire. Therefore, cutters from cemented carbides were introduced showing a much longer lifetime. Because these materials cannot be easily machined and formed, only the cutter tips were made from cemented carbides while the shank was kept steel. Figure 6 shows cutting edges of such cutters. Figure 6 (a) depicts a new cutter with a sharp edge. After 1 million cuts the cutting edge is worn to some extent, but still visually looks good and shows stable cutting results. Figure 6 (c) shows the same cutter after 1.2 million cuts. There is more wear visible, especially in the middle of the cutting edge. Nevertheless, a lifetime in the order of 1 million cuts is sufficient.

In a normal cutter design the cutting edge slides along the bonding tool side, as illustrated in Figure 6 (d). Further improvement in cutting and cutter lifetime can be achieved if a design like in Figure 6 (e) is used. The cutting edge has no contact to the bonding tool. By this the cutting edge is prevented from damage due to impact or friction contact with the hard bonding tool.

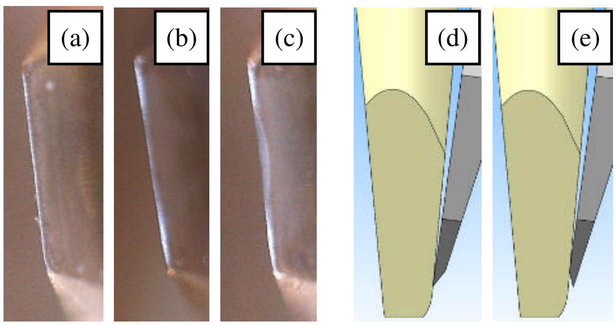

Figure 6 cutting edge, new (a), 1 million cuts (b), 1.2 million cuts (c), standard design (d), alternative design (e)

The wire guide is another important consumable in this context. This component showed only a minor need for lifetime optimization. As with the bonding tool there is no material build-up for copper bonding. The abrasive wear on the plastic material appears to be reasonably low as long as the frictional forces in the wire guide during wire feeding and looping are kept low. The initial lifetime was observed to be about half a million bonds, depending on the loop length, loop trajectory and the adjustment relative to the bonding tool. Vertical and lateral alignment as well as a proper distance to the bonding tool are mandatory. The wire should be able to smoothly slide through the wire guide opening under the V-groove. Additionally, the friction in the upper part of the wire feeding system should be low to reduce the wire feeding forces and therefore reduce frictional wear in the part where the wire is deflected.

6 Conclusion

The lifetime tests of wire bonding tools have shown wear at the wire/tool contact surfaces to occur very quickly when bonding heavy copper wire. However, in these investigations the initial wear did not cause a significant loss of bonding strength measured by shear test. Nevertheless, at some point when the abrasion of material in the V-groove has reached a critical value, tool contact with the substrate during bonding occurs. At this level of wear an investigation of the bonded area still did not show a significant reduction and still yielded high shear values. With increasing intensity of wear and tool contact with the substrate during bonding, the bond process is disturbed significantly and bond quality gets worse.

Using a tool with a cermet tip instead of tungsten carbide showed only a minor improvement in tool lifetime. A big reduction of wear could be achieved by optimizing the bonding parameters. This showed an improvement in lifetime of a factor of 4.

The highest improvement in lifetime was achieved by using a special wear resistant tool tip material. At equal bonding conditions lifetime was increased by more than a factor of 5. In combination with the optimized bonding parameters even an increase by a factor of more than 15 was possible: Half a million bonds have been made without significant visible wear and at constant bond quality. In contrast, the reference tool was strongly worn and reached its EoL in the reference process before 30k bonds.

Changing the cutter material from hardened steel to cemented carbide and improving the cutting edge geometry extended the lifetime of cutters up to the range of 1 million cuts. The change interval of the wire guide stayed around half a million bonds.

It was possible to monitor the bonding tool wear in the process signals supplied by the wire bonding machine. Using these signals a ‘wear monitor’ signal was derived. Within these investigations this signal correlated well with the visible wear, mainly abrasion at the tool tip. Further studies have to deal with the distinction between wear and other disturbances of the bond process.

This approach for monitoring bonding tool wear could be implemented into wire bonding machines in the future, helping to increase overall bond quality consistency and especially lowering overall cost by signaling optimal tool change intervals.

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