

## Copper wire bonding ready for 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. To reduce wear, different approaches are tested in long-term bonding tests. Optimized bonding tool tip geometry and tool material are two of these factors. Optimized bonding parameters were investigated as well and show a significant improvement in bonding tool lifetime. Wear and lifetime of the cutter and the 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.

### Key words

copper wire bonding, copper wire, consumable lifetime, cost per unit

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## I. 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. Besides advanced die attach techniques like sintering, copper wire bonding is used for the top side connection. Such interconnections show outstanding thermal performance and lifetime. Products with this technology are already available and increasingly more will be launched in the near future.

Copper wire as a bonding material is highly desired because of the superior material properties compared to the industry standard, aluminium wire. 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 (Si: 2.6 ppm/K, Al: 23 ppm/K, Cu: 17 ppm/K) and thus increases the lifetime and reliability of the topside die interconnection. [1], [2]

## II. Copper Wire Bonding

### A. Advantages and challenges

Today's major trends for power electronics are mainly driven by higher power density and higher junction temperatures. Besides an improved back side connection of a power semiconductor, the top side connection and the connection to the outside world must be improved. Aluminium cannot be the material of choice due to its limited electrical conductivity and temperature stability. Copper seems to be the only feasible alternative. [1], [2].

Due to the reduced lifetime of the consumables and the higher price of copper wire, the process costs are currently higher when 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 permit copper wire bonding.

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 remov-

ing the material build-up occurring during the process, and reused several times (up to a total of 1 million TDs). The same application with copper wire has a typical bonding tool change interval of less than 30,000 TDs. With copper wire there is no material build-up, but the bonding tool is worn out. The lifetime can vary from tool to tool. Therefore a TD safety factor is used to ensure flawless product quality. 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 unattractive.

From this, we can set two targets for bonding 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.

### B. Wear mechanisms

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 wire 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. To accelerate the lifetime investigations described on the following pages, only single bonds without looping were made in all experiments.

Fig. 1 (a) shows the bottom view of a new standard tool for 500 microns (20 mil) wire. This tool is made from tungsten carbide and acts as the reference for all following investigations. The corresponding top view of the bond foot is depicted in Fig. 2 (a). It shows the two contact areas from the V-groove of the bonding tool, which are mainly elliptical with a smooth matt 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 bonding tool tip and the bond foot change significantly during repeated bonding. The contact surfaces are worn out (Fig. 1 (b,c)). There is no material build-up on the bonding tool as with aluminium bonding, but rather excessive wear at the bonding surfaces of the V-groove can be observed. This can also be seen in the bond foot in Fig. 2 (b) as a 'negative' of the bonding tool tip.

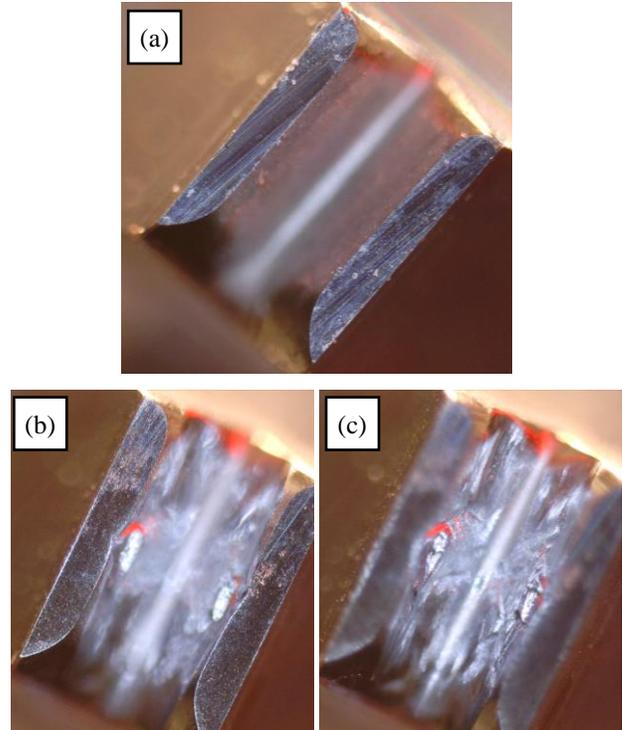


Fig. 1: Tool tip bottom view for a new reference tool (a) and after 25k bonds (b, c) with reference parameters

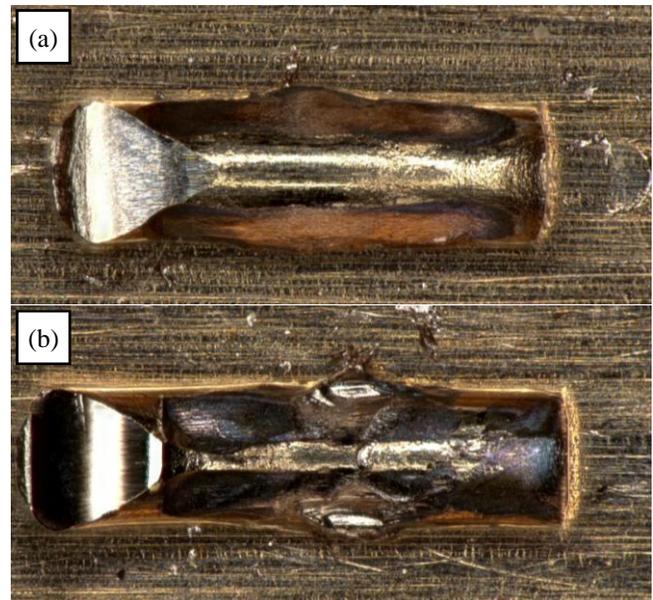


Fig. 2: Bond foot for a new reference tool (a) and after 25k bonds (b) with reference parameters

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.

It is believed the root cause of all these wear mechanisms is the locally, high mechanical pressure at the wire/tool contact zone in combination with the material parameters of copper. It is also believed that relative motion between the copper wire and the bonding tool 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. This 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-slipping”). Because of the higher Young’s Modulus of copper compared to aluminium, there is less elastic deformation and micro-slipping becomes an issue. The shiny and very smooth surfaces of the worn bonding tool tip depicted in Fig. 1 (b) supports this hypothesis. Additional indicators for this are also reported in [3] and [4].

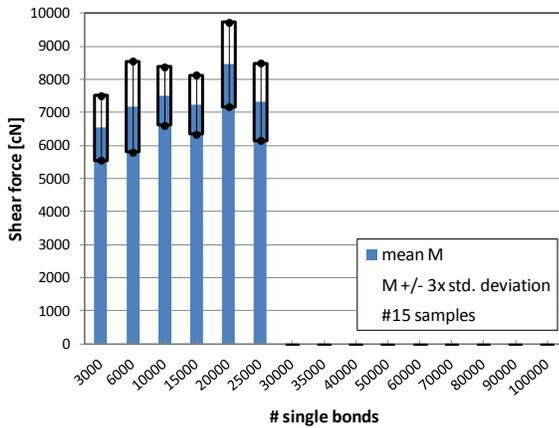


Fig. 3: Shear force bonding with reference tool and reference parameters

The observed tool wear does not directly correlate with the bond strength as Fig. 3 shows. The shear forces of bonds made after 25k bonds with the worn bonding tool shown in Fig. 1 (b,c) and Fig. 2 (b) are not yet reduced. The impacts on bond quality are examined in chapter III.C.

### III. Status Quo of Consumables

To investigate the actual status of consumables in heavy copper wire bonding, lifetime tests were conducted and analyses concerning different aspects of bond quality were performed. In this context, ‘bond quality’ is understood as a combination of optical appearance, process parameters and mechanical bonding strength.

#### A. Lifetime testing – 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 Fig. 2 and Fig. 4).

#### B. Wedge lifetime investigation

With the reference bonding tool and the reference bonding parameters, the wear of the bonding tool tip progresses quite fast as shown in chapter II.B. During this investigation an optimized parameter set for the time course of ultrasonic and bonding force have been developed. It was possible to reduce the bonding time by a factor of almost 2 from initially more than 300 milliseconds (reference parameters) to less than 200 milliseconds. Despite the shorter bonding time, optical and mechanical quality of the bonds remained. Fig. 4 depicts the quality and wear status of the bond over time. Fig. 5 correlates this to the shear values.

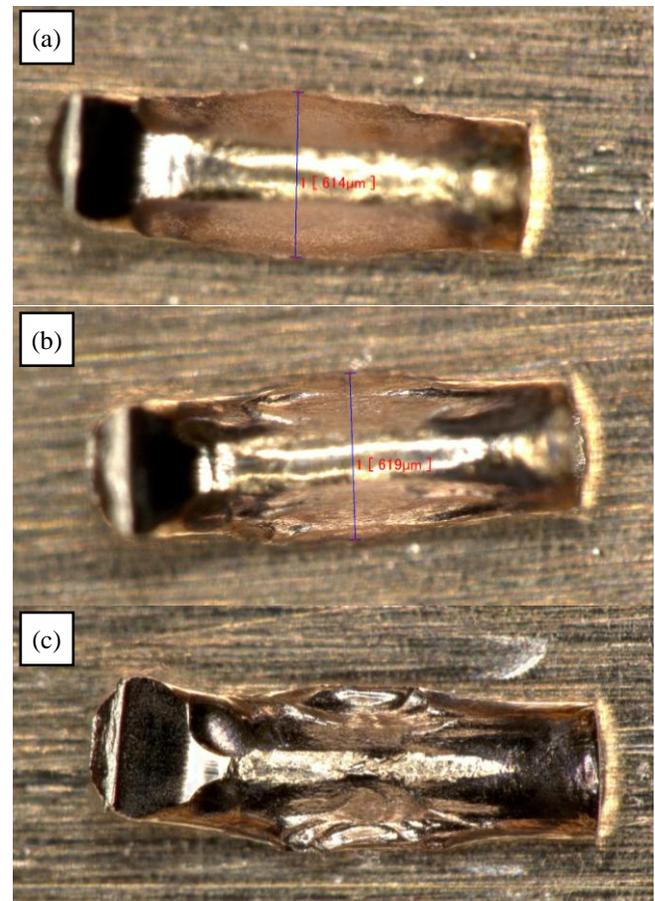


Fig. 4: Bond foot with optimized parameters with new reference tool (a), after 25k bonds (b) and after 100k bonds

Tests with other bonding tool tip material, in particular cermet<sup>1</sup>, have also been conducted ('Tool B'), but no significant improvement in lifetime was found. In [3] it is reported that the wear mechanisms are the same, but occur in a different extent. Breaking of surface material was more pronounced while abrasion and plastic deformation appeared similar to the referenced tungsten carbide material.

To suppress or at least reduce the relative motion between bonding tool and wire, a modified tool tip geometry was introduced in [5] and investigated in [3], [4]. A slightly reduced wear and a reduced process fluctuation were reported, but a significant reduction of the micro-slipping 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 optimization are ongoing and will be reported in the future.

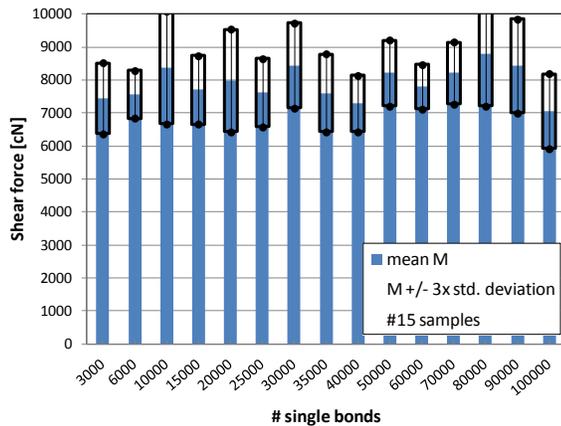


Fig. 5: Shear force bonding with reference tool and optimized parameters

### C. Impact of tool wear on bond quality

A main question in the context of bonding tool wear is the impact on bond quality. As can be seen in Fig. 2 and Fig. 4, the geometry and surface on the top side of the bond foot is changing as the tool wears. Additionally, when the wear has reached a certain level, tool contact with the substrate occurs during bonding (refer to Fig. 4 (c)). This inhibits further bond deformation and reduces the effective normal force acting on the bond. This is the ultimate signal for End-of-Life (EoL) of the bonding tool. If these touchdowns occur more frequently and with stronger impact this will reduce the bond quality and the shear values in the same degree. Such effect can be observed in Fig. 5 and Fig. 7. Here touchdowns during bonding are observed starting from

<sup>1</sup> The so called 'cermet' material is a composite of a ceramic base material in a metallic matrix.

90k bonds (Fig. 5) and 83k bonds (Fig. 7), respectively. Despite these touchdowns the shear values are reduced only by around 10%. Due to this observation an important question arises: "To what extent does the wear impact the bonding strength which is the main criteria for bond quality?"

Fig. 6 shows bond foot and shear surfaces (surface after shear test) for a new bonding tool (a) and a bonding tool which has made 100k bonds (b) (tungsten carbide tool from manufacturer C, geometry very similar to the reference tool, optimized parameters). Fig. 7 shows the corresponding shear values. Even though the contact surface towards the tool on the top side of the wire being reduced and 'poorly shaped' after 100k bonds, the effective contact area with the substrate below the 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.

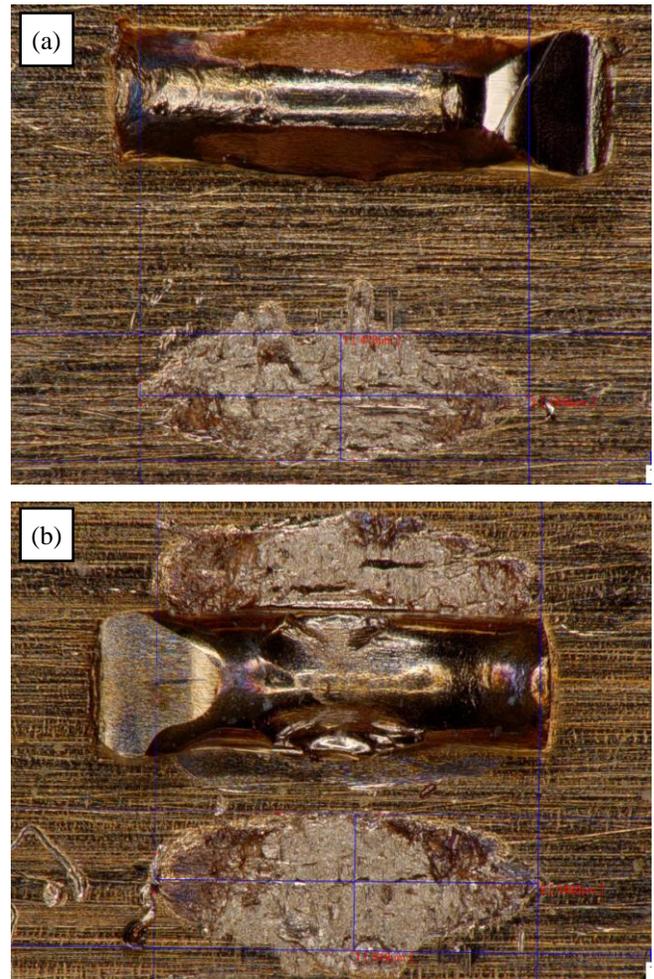


Fig. 6: Bond foot and residual bonded area with optimized parameters with new tungsten carbide tool (manufacturer C) (a) and after 100k bonds (b)

Nevertheless, the process will change with further increasing wear and to some degree, bond quality and bond strength will degrade. It should be pointed out that while the principal wear mechanisms are the same on Direct Bonded Copper (DBC) substrates, as already observed in [3], [4], the specific extent can be different for bonding on DBC. Additionally, the overall set-up of the process is important for the occurrence of tool touchdowns during bonding. If the bonds are heavily deformed right from the start, (e.g. by high force or long bonding time) tool touchdowns occur very quickly even with little bonding tool wear.

The impact of bonding tool wear on bond quality depends on the specific process, the bonding tool used and especially on the interpretation of ‘quality’. Optical appearance, process parameter deviations and mechanical bond strength can be influenced to different degrees.

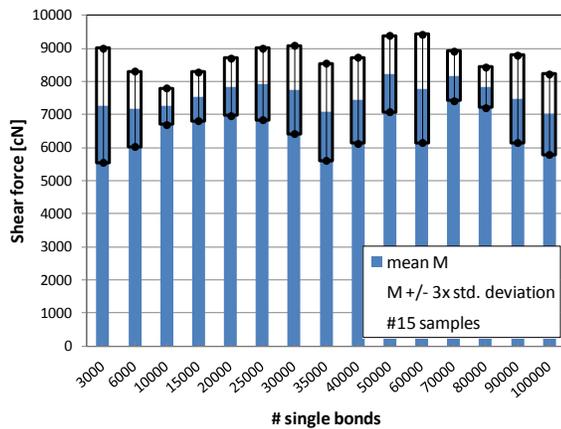


Fig. 7: Shear force bonding with tungsten carbide tool B with optimized parameters

#### D. 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. Fig. 8 shows cutting edges of such cutters. Fig. 8 (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. Fig. 8 (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.

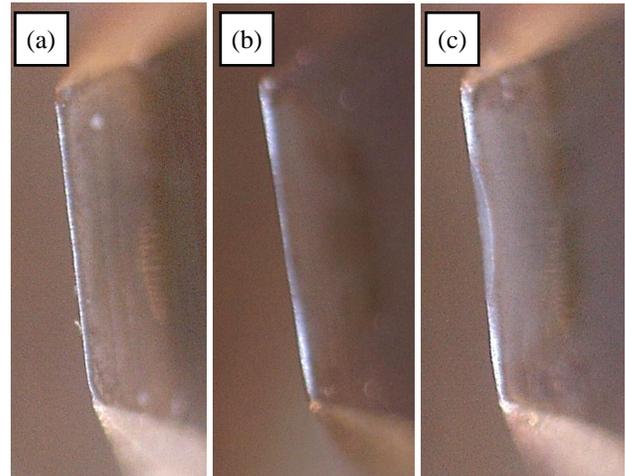


Fig. 8: cutting edge, new (a), after 1 million cuts (b) and after 1.2 million cuts (c)

In a normal cutter design the cutting edge slides along the bonding tool side, as illustrated in Fig. 9 (a). Further improvement in cutting and cutter lifetime can be achieved if a design as shown in Fig. 9 (b) 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.

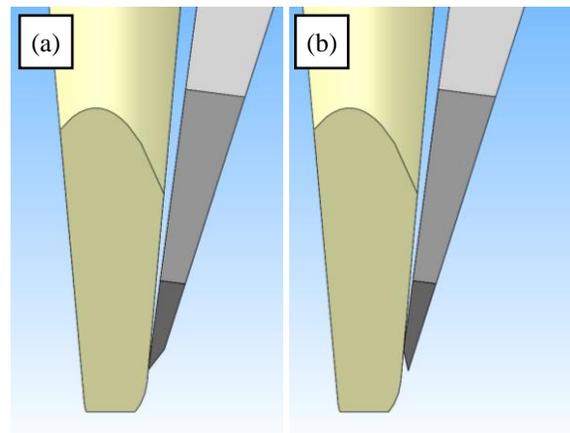


Fig. 9: Standard cutting edge (a), alternative design (b)

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 at 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 being deflected.

#### IV. Monitoring Tool Wear

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

##### A. Machine data collection and 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 the course of resonant frequency during bonding. In this study the wire bonder was equipped with a process integrated quality control system (PiQC) which includes the monitoring of an additional mechanical ultrasonic vibration signal as well as a derived friction-related signal [6], [7].

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 II.B, the geometry of the bonding tool contact area changes due to the ongoing wear. This affects the wire deformation signal.

Fig. 10 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 stays within a certain limit [7]. 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.

Such a signal should describe a mean deviation from the initial status. Because wear typically arises constantly over a large number of bonds, it is permitted to resample the data, using only every  $n$ -th quality index for the calculation. Filtering has to be of the low-pass type. Because the data is discrete and evenly spaced, a simple moving average filter can be chosen. Such a filter-window can contain hundreds of bonds. It is also possible to combine sampling reduction and filtering. Fig. 10 shows accordingly processed quality indices.

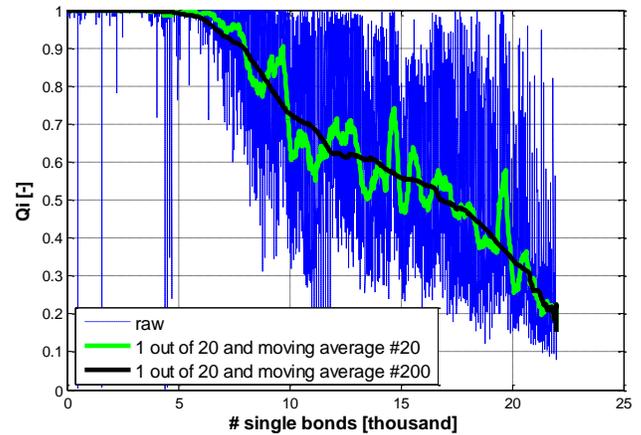


Fig. 10: Course of quality index and deriving a wear monitor signal

The raw data would not be appropriate to react upon a specific value because of the fluctuations. Fig. 10 shows two filter approaches with sampling reduced by a factor of 20 and moving average filters of width 20 and 200, respectively. The latter combination was found to be a good wear monitor signal.

##### B. Correlation between wear and machine process data

This approach was tested for different bonding tool and parameter set-ups. Fig. 11 shows the course of the calculated wear monitor signal for two bonding tools, one tungsten carbide tool (‘Tool A’) and the other with identical geometry but with a cermet tip (‘Tool B’). Tool A was tested with reference parameters and with the optimized parameters. This data corresponds to the tests described in chapter II.B and III.B (Fig. 1 to 5). The reference 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 Fig. 1 and 2. An identical tool reached 4 times this number of bonds when optimized parameters are used. This is seen in Fig. 4. Tool B with the cermet tip was also tested and monitored. As described in chapter III.B no significant improvement in lifetime was found using classic methods (optical inspection, shear force). This also correlates with the results shown in Fig. 11.

For other bonding tool types with different foot shapes the results and the sensitivity were different. A bonding tool EoL-threshold (End-of-Life) for the wear monitor signal is only valid for one specific set-up. Another point which can have an influence on this signal is mechanical adjustments of cutter and wire guide. 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.

Instead of the wire deformation quality index the overall quality index can also be used. The sensitivity will be different, typically lower, because other signals are influenced by wear only in minor degrees. But the multitude of used physical signals will increase the baseline for judging the wear status and could therefore yield more confidence.

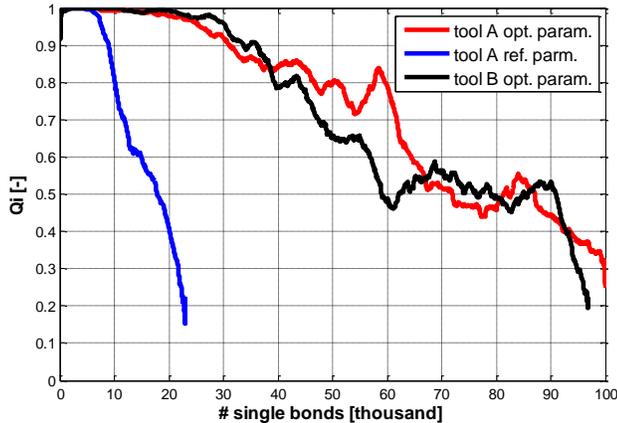


Fig. 11: Wear monitor signal up to 100k bonds

### C. Optimal tool change interval via wear monitor

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.

What is 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.

## V. 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 the 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 residual bonded area after shear test 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 will get 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.

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 bonding 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 bonding quality consistency and especially lowering overall costs by signaling optimal tool change intervals.

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