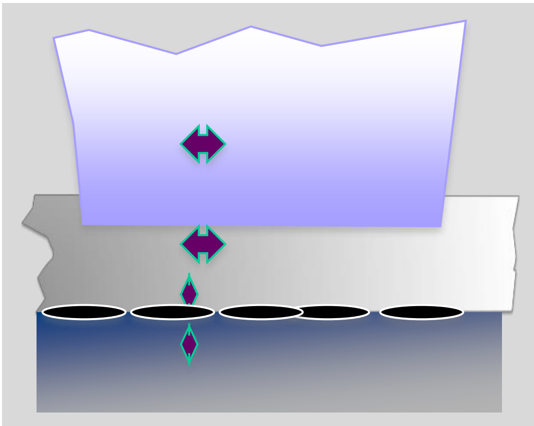
Staying Ahead in Bonding Technology

F&K DELVOTEC

Which Frequency is Best for Wirebonding?

Technical Note 2015/01



Abstract

In industrial practice, frequencies from 40 kHz up to 160 kHz are currently employed for wire-bonding while for experimental purposes, lower and higher frequencies from around 25 kHz up to 300 kHz are discussed. Typically, heavy aluminum wire or ribbon is preferably bonded at lower frequencies between 40 and 80 kHz, while thin aluminum or gold wires are wedge- or ball-bonded at frequencies between 100 and 140 kHz.

We present a discussion of the pros and cons of different ultrasonic frequencies by looking at the mechanics during the bonding process. Higher frequencies allow shorter bonding times and permit bonding on more sensitive surfaces, but suffer from a narrower parameter window. This is mainly due to the smaller vibration amplitudes at the tool tip which can be employed for higher frequencies. The major benefit for many applications is that higher bond quality is possible even at lower wire deformation which additionally creates a healthier bond heel. Lower frequencies, on the other hand, seem to have advantages for rougher surfaces where some planarizing and smoothing is required before bonding can begin to take place, while running a higher risk of damaging the bond after forming it.

What happens during regular bond formation?

It is a good starting point to discuss in some detail the physical processes happening during the different stages of bond formation. Figs. 1 through 3 give a schematic representation of typical steps for wedge bonding, but the principal features hold also for ball-bonding.

Once the bond tool and the wire have touched the surface to be bonded, the ultrasonic (US) vibration is turned on, resulting in an oscillation with a characteristic amplitude of 1 to 2 µm for thin-wire bonding and about 3 to 5 µm for heavy wire bonding.

The crucial aspect is that the wire and the tool move together as one unit, and therefore the wire scrapes along the bonding surface. For this to work reliably, the tool has to adhere to the wire far better than to the bonding surface after the touchdown step, and normally this is assured by the matte surface of the bond tool which will imprint somewhat onto the top wire surface due to the touchdown force which is defined in the bonder settings. (For gold wedge-wedge bonding, the wedge foot very frequently contains a cross groove to generate a better grip.)

The first few milliseconds of US action will cause a scraping action of wire against bondpad which cleans the surface of contamination and surface oxides and exposes the atomic lattices of wire and bondpads to each other. In the case of Aluminum wire and bondpads, this is helped by the fact that Aluminum is always covered by an oxide layer which is both very thin and very hard. It therefore acts as a sort of grinding powder which helps to expose the atomic lattices very quickly, but does not generate much debris because there is so little abrasive material (oxide) due to its thinness. This is the underlying reason why aluminum wire can so easily be bonded at room temperature without additional thermal activation (such as is required by gold wire).

Once the exposed atomic lattices have come into close contact with each other, intermetallic bonding on an atomic scale begins to take place, and small bond islands begin to form (shown in Fig. 2 as small black ovals). These islands now change the behavior of the wire, because now the wire no longer moves as rigid bulk matter with the top and bottom surfaces in tandem. Rather, the bottom surface becomes immobilized more and more while the top surface still moves: the wire is deformed non-elastically and worked. (The resulting work hardening, dislocation creation and other effects are ignored here.) It is important to note that the motion inside the wire bulk is almost entirely plastic deformation, not elastic, because there the amplitude difference of roughly 1 µm across a bulk thickness of typically 25 to 30 µm (the wire diameter) is way beyond the elastic deformation limit of aluminum. The small double arrows in figs. 1 to 3 also indicate a measure of the resulting amplitude at the various interfaces, showing that as more and more bond islands form, the amplitude at the bottom side of the wire decreases relative to the top side, compared to the initial phase. So does the amplitude overall, including the tool tip, due to the damping action of the bond formation.

As the US vibration continues, the bonding islands become larger and larger (in the ideal case, they fill the entire contact area between wire and bondpad) and therefore the relative motion between the the wire and the bondpad ceases. In fact, the surfaces of wire and bondpad now move in lockstep and the bondpad starts to oscillate, albeit at a much lower amplitude, as indicated in Fig. 3.

During this process of increasing bond coverage, the tool presses into the wire and deforms it to lower height and correspondingly greater width. This deformation in the Z axis can be monitored by the bonder, usually in a time-resolved fashion, and it provides an excellent quality control tool by recording the end deformation after the programmed bond time, and by monitoring the deformation speed over time. In a more sophisticated version developed and offered by F&K Delvotec, this deformation curve is used to feed a control loop which turns the US power higher or lower if the deformation runs ahead or behind a programmed standard curve. This patented Bond Process Control (BPC) allows an automatic fine-tuning of the bonding process to avoid under- and overbonding.

The bond time is usually programmed so that US power is applied longer than required to fully form the bond. The extra US time is usually referred to as a "tempering" period which works the bonding zone without further vertical deformation of the wire. Looking at the vibration across the entire bonding system in Fig. 3 shows that the oscillations now pervade the entire system, but with a higher amplitude at the tool and top surface of the wire, and with lower amplitude at the bottom surface and bond pad. The important aspect to note is again that tool and wire surface move in lockstep, and that bottom wire surface and bondpad also move together. The amplitude gradient across the wire causes cold working of the bulk metal which is considered vital in allowing the dislocations generated from bonding to diffuse into a larger interface zone, a beneficial effect for the lifetime of the bond.

It might be noted that during this entire discussion there has been no mention of a melting zone at the interface, nor even of a temperature rise due to the friction generated between wire and bondpad. Indeed, lots of research effort have been directed at identifying and quantifying such a temperature rise at the interface during bonding, with very inconclusive results. Attempts at finding evidence of molten zones, however small, in micrographic sections of the interface have been even less successful. One may conclude, therefore, that whatever thermal effects may be involved, they must be very small. In fact it is instructive to realize that aluminum wire was successfully bonded at the temperature of liquid nitrogen – if temperature had any effect, it would surely show up under such drastic conditions.

One might question the model discussed above, especially as concerns the “stickiness” between bond tool and wire surface at all times, and one might argue that at least during the final or tempering phase the bond tool glides across the wire surface rather than working the wire bulk. Three points argue against this: first, it is well known that reducing the bond force will easily provoke a poorer contact between wire and tool once the bond is formed. The tool will then glide along the surface, no longer working the wire but performing a grinding or polishing motion, leaving what is known as a “burnt” wire bond surface. Secondly, in cases where the bond pad metallization itself is not well connected to the substructure, it is susceptible to being torn off by the oscillation amplitude imparted to it, resulting in what is called a metallization lift-off. Thirdly and most tellingly, micro-video films of impressive quality have been made at the Fraunhofer IZM institute in Berlin by the group of Lang and Schneider-Ramelow showing the bond process at slow-motion and high magnification. These micro-videos clearly show the steps according to the model described above, from the in-sync motion of wire and tool in the first phase to the decreasing amplitude from the tool downward but reaching into the bond pad during tempering. The same results are seen in laser vibrometer measurements following the vibration amplitude (and frequency) at the tool tip, at the wire end, and at the bond pad edge during the bond process.

Bonding materials behave differently at different bond frequencies

No mention was made about the US frequency during the preceding discussion. In practice, frequencies between 40 kHz and 160 kHz are used, with a clear preponderance of lower frequencies around 60 kHz for heavy wire bonding and higher frequencies (100 and 140 kHz) for thin-wire bonding, both wedge- and ball-bonding.

In the past, there was widespread discussion about bonding at higher frequencies up to 300 kHz. This was considered attractive especially for gold-ball bonding because it was considered possible to bond at or close to room temperature, in effect replacing heat by US frequency. While some success was made, the process always suffered from the chief weakness of having a much smaller parameter window and hence lost more in robustness than it gained in cost. Today there is very little discussion about this topic.

What does, however, find wide discussion are the different strengths and weaknesses of the different bonding frequencies. To begin with, a higher US frequency will of course shorten the time needed for bonding. This is because a bond requires a certain number of oscillations (or rubbing motions) to form well – in the order of 1000 to 3000 (using a typical bond time of 20 ms at 100 kHz). A higher US frequency reaches this number of oscillations in a proportionally shorter time. While of some influence on the process productivity, the bond time itself only accounts for at most half the cycle time and therefore has no big influence.

More importantly in practice, it appears that at a higher US frequency, lower vibration amplitudes are sufficient for successful bond formation. (This is not to say that higher frequencies automatically generate lower amplitudes – it is purely a matter of parameter settings.) The physics also imply that at higher US frequency the motion of the tool tip (and all other motions associated with it) will be faster. We will discuss these two aspects in turn.

Larger motion amplitudes seem to help smoothing rougher surfaces while they appear to have higher risk of damaging delicate surfaces. Therefore, in our experience rough bond pads such as thick film hybrid pastes often profit from a planarizing action of the larger amplitudes at lower US frequency of 60 kHz. On the other hand, very thin, delicate or smooth bond pads such as the metallizations of SAW filters which can be as thin as 40 nm Aluminum, are bonded with advantage at a higher frequency of 140 kHz. In our experience, 100 kHz seems to be a happy medium which works well for the majority of applications, and indeed the majority of our thin wire bonders are shipped with this US frequency.

Higher US frequency means that tool tip and all other parts of the bond setup move at higher speed (for sinusoidal oscillations, the maximum motion velocity is proportional to the frequency). Empirically speaking, most bonding materials, including the bonding wire, behave under higher US frequency as if they were harder or stiffer, compared to lower frequencies. From the practical point of view this looks like the bonding frequency penetrating less deeply into the bulk material. In our experience, therefore, softer materials such as Kapton foil, are often bonded better at higher frequencies. The same is true for some sensor dies or SAW filters which, while themselves hard, are mounted on soft or very soft silicone glues in order to allow mechanical decoupling. By standard wisdom, they ought to be impossible to bond but they turn out to be surprisingly easily processed with the right parameter setup, and they, too are usually bonded at higher frequency. Again on the other hand, bond wires typically appear softer at lower frequencies and therefore are more easily shaped and adapted to the bond pad surface, improving the bond in cases like the rough thick film surfaces mentioned above. Table 1 gives a short overview of the typical preferences we find in practice.

In case of ...	frequency
Soft substrates (Kevlar)	higher
Moving die (sensors)	higher
Rough surface (thick film)	lower
Thin metallization	higher
Harder metallization	higher
Thinner wire	higher
Harder wire / softer wire	----

Table 1: Typical material and US frequency choices

One additional, and rather important, advantage of higher US frequencies is, all other things being equal, that a good bond is already achieved at lower wire deformation. This is in keeping with the observation that at higher US frequency the wire behaves as if it were harder. A bond with lower deformation is always preferable to a bond of identical shear strength but higher deformation because the heel will suffer less, leading to superior long-time performance and lifetime. This is also borne out by the observation that, at least for Al wires, pull-test values decrease with increasing wire deformation.

Another general observation about higher US frequencies, however, is that the parameter window is usually smaller than for lower frequencies. This can be to a larger or smaller degree and needs to be weighed carefully against the advantages.

As a bonder manufacturer, we therefore find it advantageous to have a range of US frequencies to choose from, and the following Table 2 lists the most popular frequencies chosen in practice. Some exotic frequencies are available in addition but are of no relevance in the marketplace. Note that for modern wire-bonders, only the US transducer has to be exchanged when switching frequencies (since the transducer has to have a mechanical resonance at the desired frequency and therefore is mechanically different from a transducer at a different frequency). The US generator is usually digital and hence has freely programmable frequencies. A change of US frequency can be performed at low cost by the bonder operator.

Gold-Ball		60	**100**	120	140
Thin Wedge		**60**	**100**	120	**140**
Heavy Wire	40	**60**	90	**120**	

Table 2: Typical material and US frequency choices

Recommendations

Very broadly speaking, one should use a frequency as high as possible and as low as necessary. Higher frequencies allow shorter bonding times and permit bonding on more sensitive surfaces, but suffer from a narrower parameter window. Rougher surfaces often are bonded better at lower frequencies.

For further information and discussion of particular problems, readers are invited to contact F&K Delvotec directly.

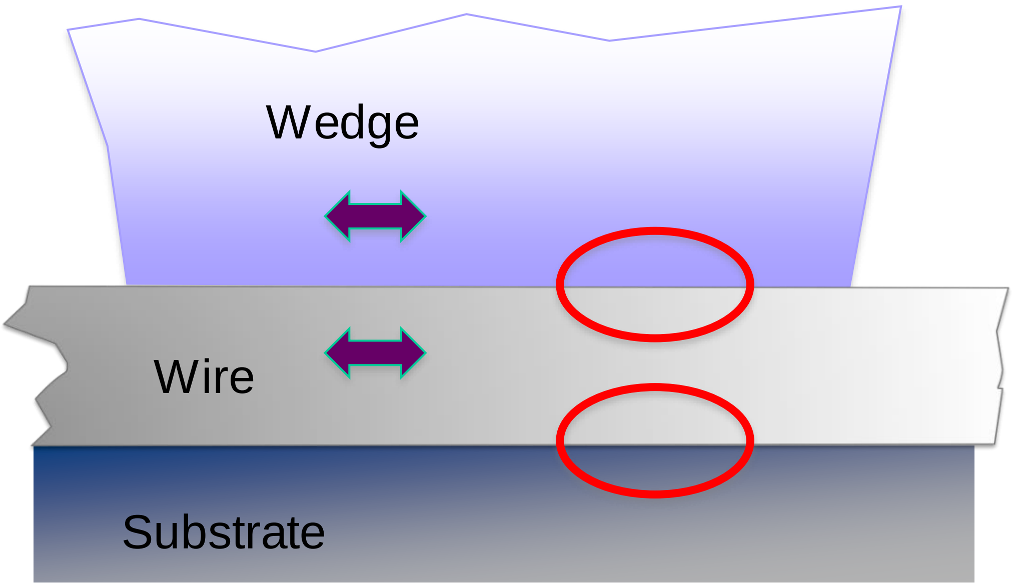


Fig. 1 First or cleaning phase of wedge bonding

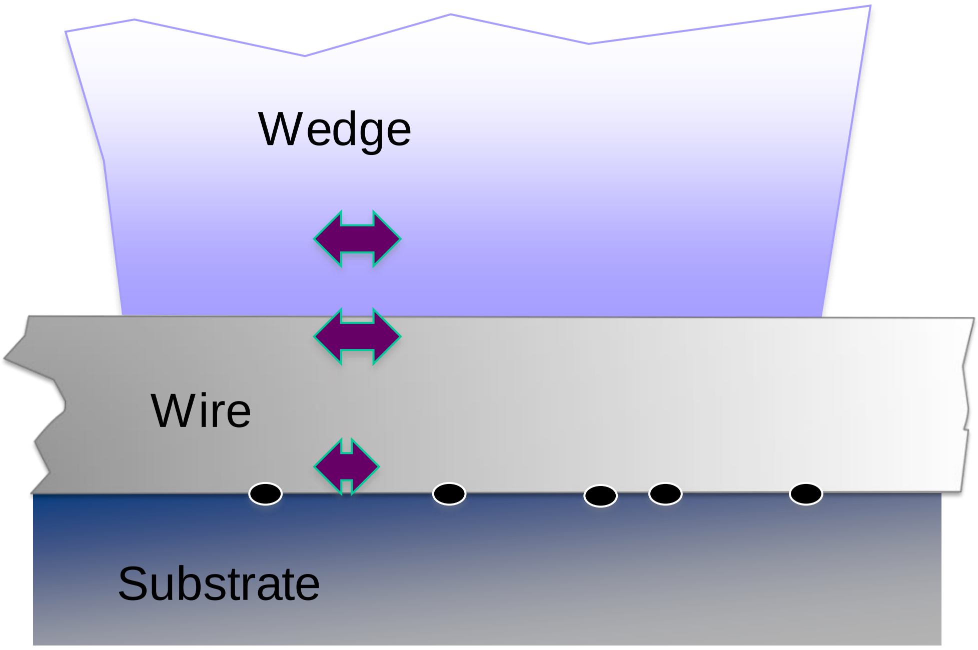


Fig. 2 Second or incipient bonding phase of wedge bonding

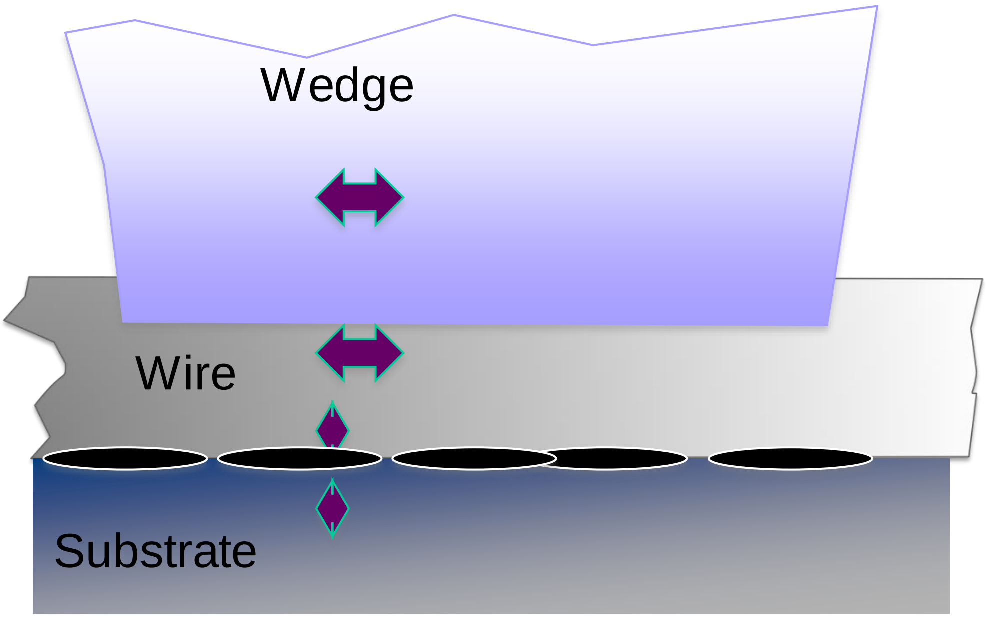


Fig. 3 Bond formation phase of wedge bonding

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