APPLICATION NOTE

Improvement of a DoE for wire bonding process optimization through the use of the BAMFIT method*

Process optimization in wire bonding begins with the (ideally systematic) adjustment of the bonding parameters and the determination of the bond quality on the basis of quantifiable parameters. Among others, these include the deformation of the bonding contact, as well as the measured pull/shear forces and fracture patterns in the destructive test (according to DVS data sheet 2811, version 2/2017). It is known that the individual test results are of limited significance, or that each test has certain limitations.

Now, the purpose of this Application Note is not to discuss these limitations, but rather to show the possibilities that are now available through new methods. One such new method is BAMFIT – Bondtec Accelerated Mechanical Fatigue Interface Testing. In this process, the bond contact is subjected to a mechanical cyclical load with the aid of ultrasonically excited pliers and is thus detached from the surface within a few seconds. The crack caused by the cyclical load proceeds from the edges of the bond interface into the bulk wire. It is currently assumed that the crack initiates exactly at the point where the bonding zone (bond interface) generated during the bonding process ends.

In the experiment presented here, the bonding parameters for a 300 µm Al thick wire on a copper sheet were optimized using DoE methodology (Design of Experiment). To assess the achievable bond quality, shear test and the BAMFIT method were used. The basic process settings are summarized in the grey box at the bottom right. For an explanation of the parameters, see Figure 1. The following bonding parameters were selected as input variables for the DoE (the modified process variables or bonding parameters):

- US-Power
- Ramp Time
- Ramp End Force
- Burst Time

As response values (measurable process/quality parameters) were defined:

- Shear force
- Signal of the deformation sensor (the lower the value, the less deformed is the bond contact)
- BAMFIT number of cycles
- Interconnected interface area (fracture pattern after BAMFIT test)
- Length/width ratio of the interface

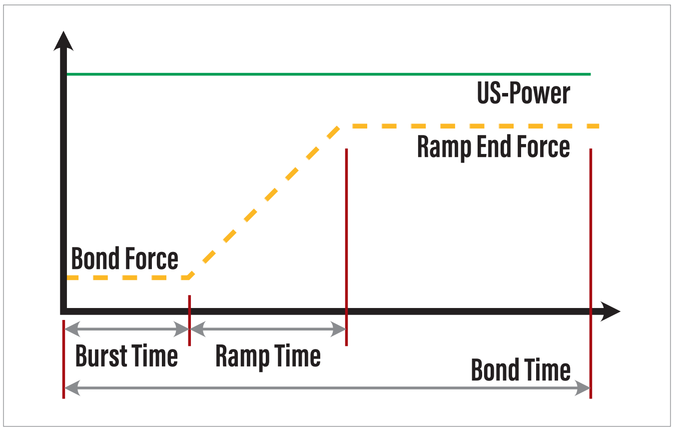

Figure 1: Explanation of the parameters during the bonding phase

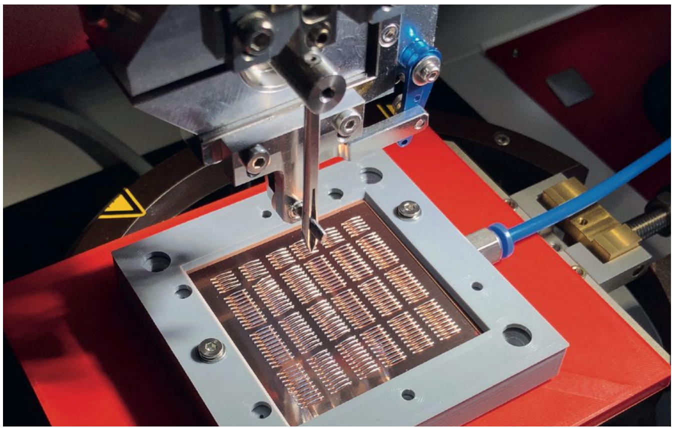

Figure 2: Setup – substrat, bonding layout, clamping and BAMFIT head

Bonding and testing parameters
Touchdown Force: 300 cN
Bond Time: 140 ms
Bond Force: 300 cN
Ramp End Force (varied): 500 – 900 cN
US-Power (varied): 110 – 210 digits
Ramp-Time (varied): 20 – 100 ms
Burst-Time (varied) 1 – 37 ms
Default-Force: 300 cN
Wire bonder: F&S Bondtec 5850
Bonding wire: Heraeus Al-H11 300 µm, RL 318 cN, D 22,7%
Bonding frequency: 58 KHz
Shear tester: F&S Bondtec 5600
Shear tool: width 1,2 mm
Shear height: 30 µm (10% wire diameter)
BAMFIT-Tester: F&S Bondtec (58 kHz)
BAMFIT US-setting: 70 digits
BAMFIT pre-load: 40 cN
BAMFIT clamping-height: 30 µm (10% wire diameter)

*The BAMFIT method has been developed by TU-Vienna. Patent number: DE102016107028A1

The copper sheet was covered with a foil to protect it from oxidation and mechanical damage. This protective film was removed just before the bonding process but the surface was not cleaned separately, although slight irregular shading was visible in the oblique view – reality is not optimal and this should also be reproduced in the experiment. The bond contacts were arranged one above the other on the copper sheet in a column, so that a complete DoE parameter variation could be performed in this column. At the beginning of the column, five additional bond connections were generated as dummy wires. This means that these contacts were not included in the tests at a later stage, but were meant to ensure that the system had settled before bonding the bond contacts under investigation. This column was bonded a total of 6 times, so that 6 measured values were available for each parameter combination (bond layout, see Figure 2). A randomisation of the DoE plan was deliberately not carried out in order to facilitate a later allocation and analysis of the individual tested bond locations. The bonding process takes place without interruption, and the wire deformation signal was recorded and stored for each individual bond contact. Both shear test and BAMFIT test were performed fully automatic. Since both tests are destructive processes, separate copper sheets with bond contacts were produced for each test. The shear and BAMFIT values were measured and stored for each individual bond contact. The connected interface area was then measured on the light microscope at the bond contacts destroyed by the BAMFIT method. The entire examination was carried out exclusively on the second bond contact (2nd bond, destination bond).

The average values of the measured results are summarized in Table 1. The DoE evaluation was based on the individual values, the complete listing of which would, however, go beyond the scope of this publication.

Table 1: Testing results (mean values)

DoE run	DoE point type	US-Power [digits]	Ramp Time [ms]	Ramp End Force [cN]	Burst Time [ms]	Shear force [cN]	Deformation [digits]	BAMFIT number of cycles [number]	Interface area [µm²]	BAMFIT cycles / interface area [1/µm²]	Ratio interface Length/Width [µm/µm]
1	1	185	40	600	10	1128	8511	54758	122170	0,44882	1,30
2	1	135	80	600	10	1024	6664	24845	106399	0,23338	1,71
3	1	135	40	800	10	1198	8468	32398	133009	0,24259	1,88
4	1	185	80	800	10	1204	9757	93918	142885	0,65750	1,36
5	1	135	40	600	28	1016	6675	29805	106253	0,27904	1,85
6	1	185	80	600	28	1098	8240	58594	119027	0,49133	1,28
7	1	185	40	800	28	1169	9679	97948	143468	0,68073	1,38
8	1	135	80	800	28	1065	7794	37627	122836	0,30495	1,89
9	0	160	60	700	19	1135	8083	65266	128437	0,50742	1,57
10	0	160	60	700	19	1138	8134	56483	128008	0,44060	1,54
11	1	135	40	600	10	1018	6660	26001	109879	0,23569	1,75
12	1	185	80	600	10	1113	8277	66418	120790	0,54912	1,21
13	1	185	40	800	10	1192	9885	99426	147334	0,67421	1,38
14	1	135	80	800	10	1157	7832	34009	128541	0,26433	1,83
15	1	185	40	600	28	1112	8353	68048	122630	0,55483	1,25
16	1	135	80	600	28	1003	6505	24744	104515	0,23702	1,75
17	1	135	40	800	28	1132	8003	46027	131564	0,34940	1,84
18	1	185	80	800	28	1169	9490	100103	141467	0,70707	1,36
19	0	160	60	700	19	1155	8144	64028	129684	0,49255	1,51
20	0	160	60	700	19	1162	8286	67373	128179	0,52548	1,49
21	-1	110	60	700	19	862	6321	12941	102699	0,12480	2,22
22	-1	210	60	700	19	1115	9670	106898	138948	0,76792	1,09
23	-1	160	20	700	19	1183	8264	67945	133471	0,50715	1,51
24	-1	160	100	700	19	1127	7863	67083	126877	0,52728	1,55
25	-1	160	60	500	19	980	6807	40092	101955	0,39222	1,35
26	-1	160	60	900	19	1245	9570	86087	146099	0,58918	1,54
27	-1	160	60	700	1	1202	8187	52339	130630	0,40100	1,55
28	-1	160	60	700	37	1153	7997	56608	122497	0,46136	1,51
29	0	160	60	700	19	1184	8184	61901	128661	0,48176	1,48
30	0	160	60	700	19	1172	8045	60125	128764	0,46717	1,51

The shear code, i.e. the fracture pattern in the shear test, was not included in the evaluation. Typically, the shear code is divided into classes (usually 4). Such classes (or factorial groups) can only be evaluated to a limited extent in a DoE. Continuous measured values, such as areas, are better. Determining the shear area and the shear residue would also have been an option. However, this was not done because there are uncertainties in the measurement of the shear area. These uncertainties are caused by the „ears“ (areas pressed out sideways from a thick wire bond) that form during the bonding process. These protrude clearly beyond the bond interface, but do not contribute to the bond strength. To put it another way: In the area of the „ears“ no connection is formed but in the shear residue, the sheared „ears“ are still clearly recognizable. Figure 3 demonstrates this fact by comparing the fracture surfaces after the shear test and the BAMFIT test. After the shear test, a wire material residue remains where an „ear“ was located. However, no connection was formed under this region and therefore this area does not contribute to the strength of the bond or its shear force. An evaluation of this remaining socket area would therefore carry a systematic error, which would depend on the deformation of the bond and which also increases with increasing deformation.

In addition to the interface surface, the shape of the interface was also included in the evaluation. This shape is determined by the ratio of interface length and interface width. If this ratio is in the range 1.5 – 2, the interface has an elliptical shape, while a value closer to 1 indicates a circular shape (see Figure 4). At present, the author is not aware of any publications discussing the effect of the shape of a wire bond interface on connection quality and reliability. Based on experience, a uniform elliptical shape should probably be sought.

The DoE was evaluated with the software Minitab v17. Measurement outliers were not eliminated because clearly recognizable errors due to system malfunctions did not occur. Subsequently, the evaluations were carried out for the individual response values, non-significant terms were eliminated and it was checked whether the models determined show meaningful correlations. The main effects determined are summarized graphically in Figure 5. The bond parameters US Power and Ramp End Force show the largest gradients, i.e. these effects have the most significant influence on the respective response value. In order to make an exemplary evaluation and draw conclusions in this publication, the contour diagrams for these two bond parameters (US Power and Ramp End Force) are summarized in Figure 6. These show which value the respective response value assumes when the two bond parameters are set. The other two input variables (Ramp Time and Burst Time) were set in the software to fixed values of Ramp Time = 85 ms and Burst Time = 23 ms.

Shear force and deformation of the bonds increase with higher settings for the bond parameters (contour diagram in Figure 6 – left and center in the upper line). The increasing Ramp End Force provides a more intimate contact of the surfaces of the connection partners (wire and surface), whereas the increasing US power provides the energy input required to form the connection (friction energy, softening of the wire material, mobilization of lattice defects, input of lattice vibration). Beyond a US power of 170 - 180 digits, the measured shear force decreases again. This is probably caused by the increasing softening of the wire material in the bond region higher ultrasonic input. The shear tool can

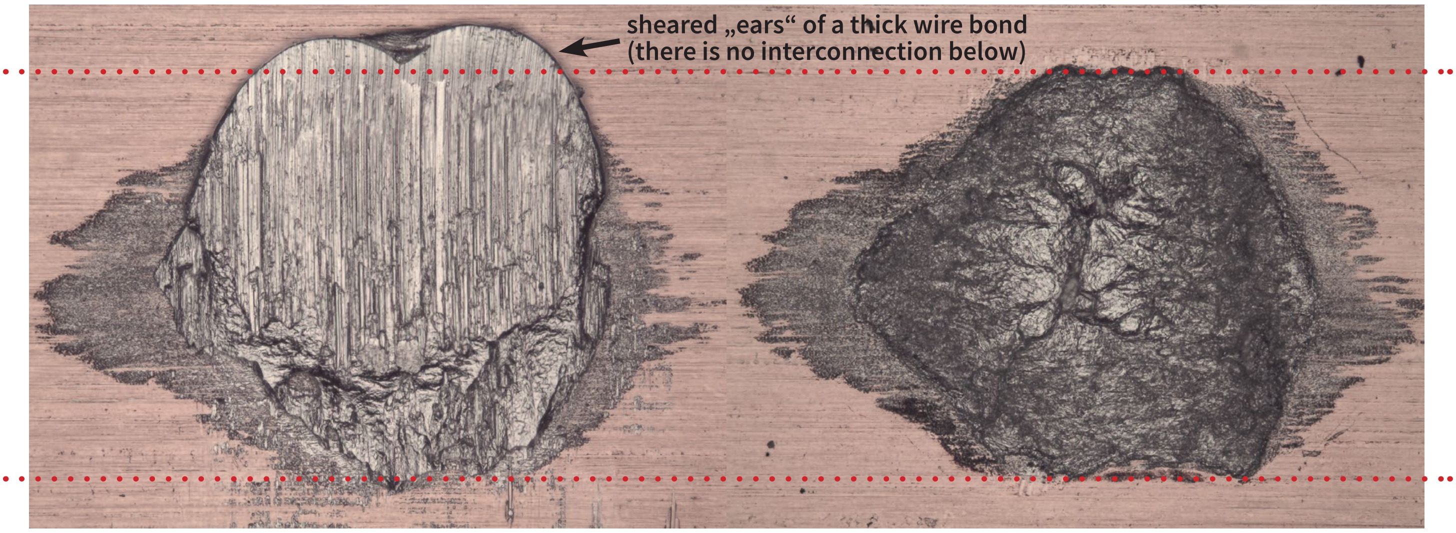

Figure 3: Comparison of shear area width – shear fracture pattern (left), BAMFIT fracture pattern (right)

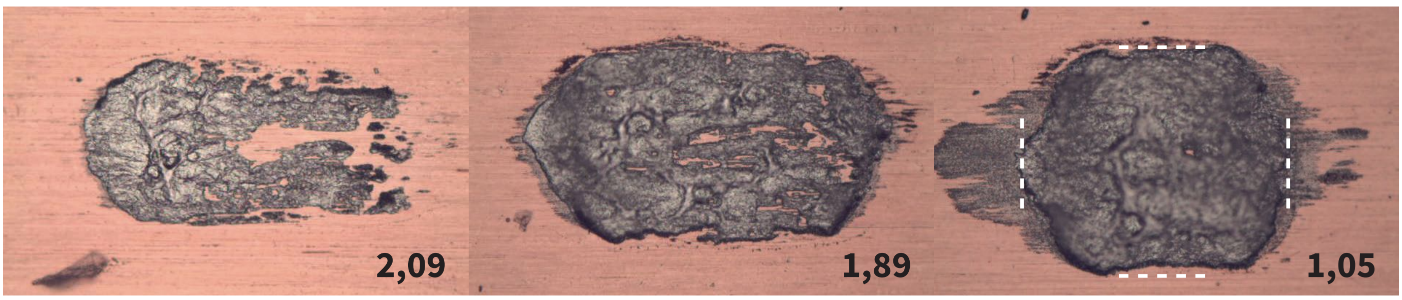

Figure 4: Interface area (after BAMFIT) with different ratio of interface length (left to right) to interface width (top to bottom)

penetrate this deformed wire material much more easily or with lower resistance. This means that the shear test can only make a statement about the strength of the bond interface as a function of the condition of the wire material. This limits the significance of the test for some questions. A maximum shear force is found at an average US power of approx. 165 digits.

Wire deformation increases steadily with increasing bond parameters. The development of the interface area is similar. However, the interface area plot shows that from a certain value for the US Power there is no further increase in the interface area. This value is about 180 digits. Only with an increase of the Ramp End Force a further increase of the interface area can be achieved.

The BAMFIT cycles reach a maximum with the highest settings for US Power and Ramp End Force. Furthermore it can be seen that a US Power of at least 160 digits should be selected. Below this US level, a change of the Ramp End Force causes only an insignificant increase of the BAMFIT cycle number. Beyond a US Power setting of 160 digits and the Ramp End Force of 700 cN, the BAMFIT cycle number increases continuously with a parameter increase, with a maximum at the highest settings for both parameters. The BAMFIT test therefore does not show the behaviour observed at the shear test. The increasing softening of the wire material at the higher bond parameter settings obviously has no influence on the test itself.

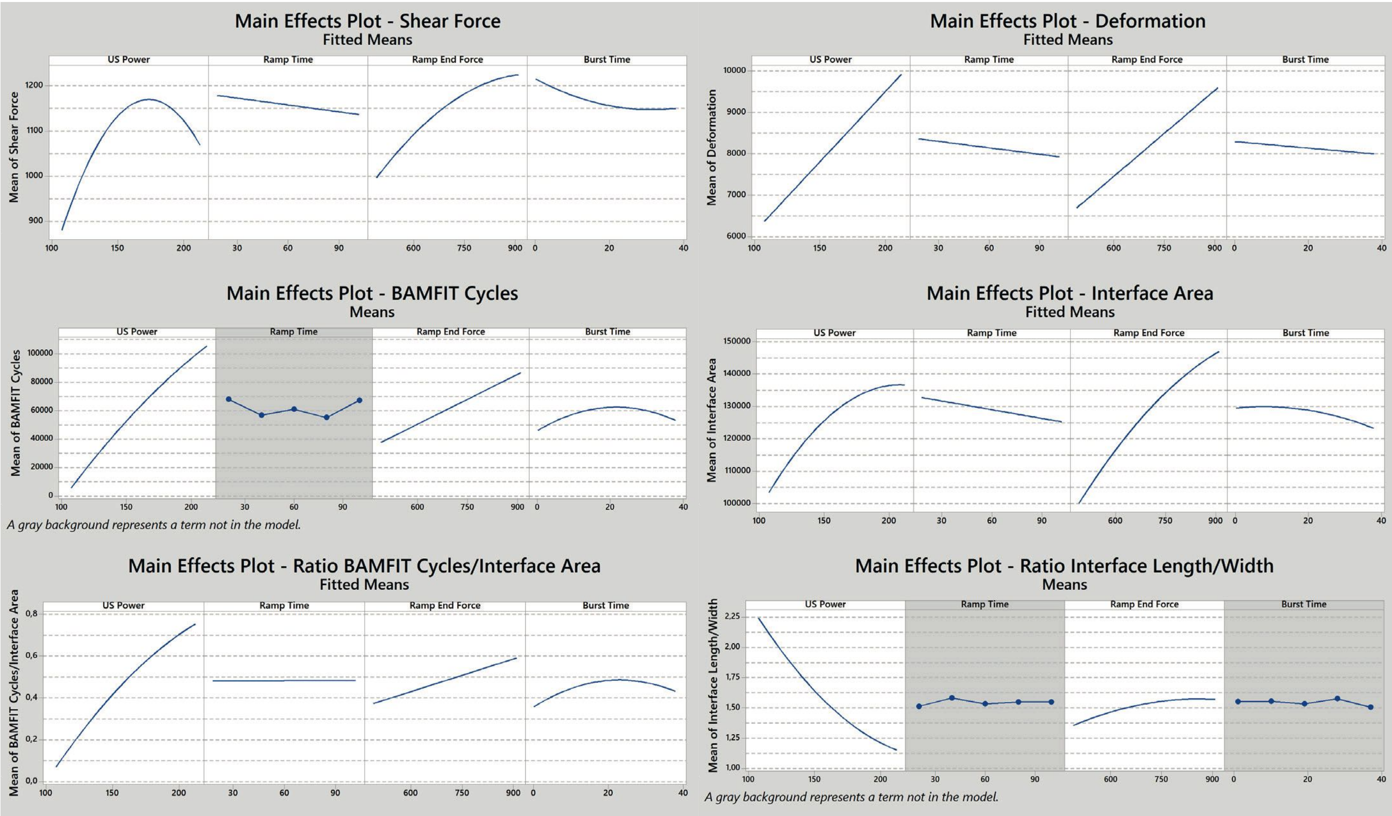

Figure 5: Main effect diagram for all six selected response variables (interactions found are ot displayed due to limited space in this publication)

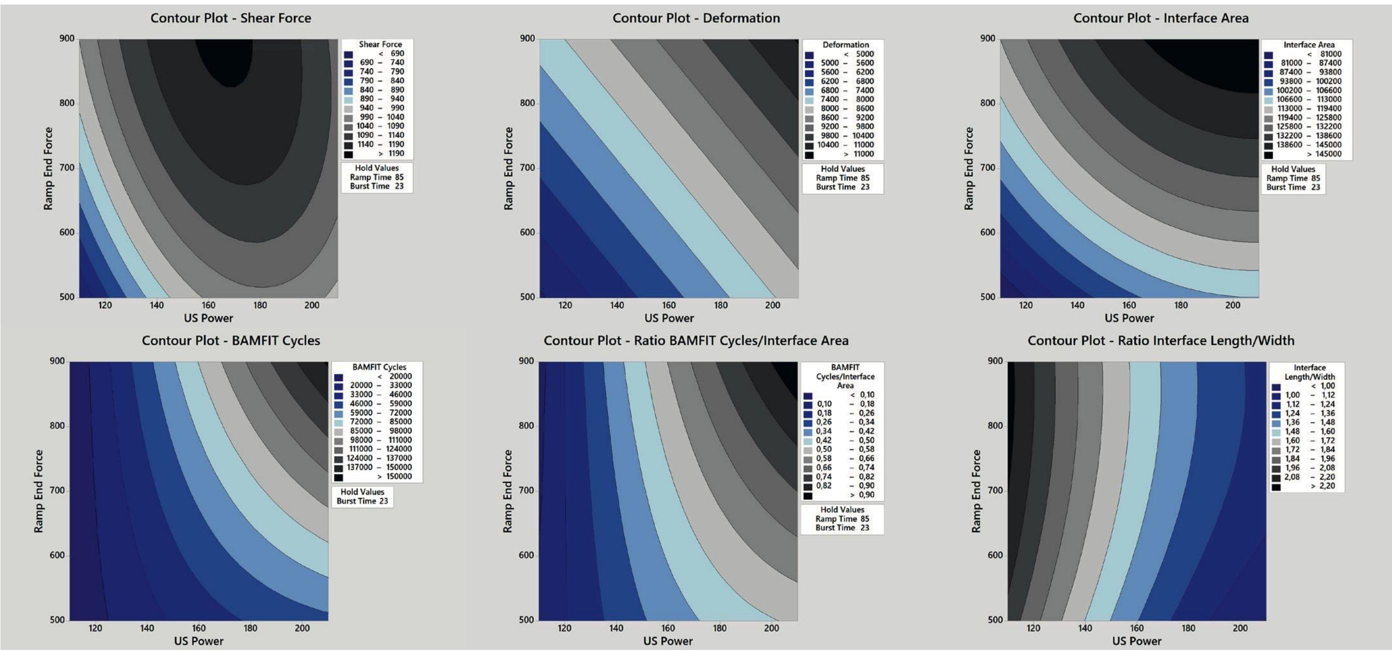

Figure 6: Contour diagram – using the example of US Power vs. Ramp End Force – for all six selected response variables

Since interface area and BAMFIT number of cycles develop very similarly, the ratio of the two values is highest at high bond parameter settings and lowest at low bond parameter settings. In order to achieve a high BAMFIT cycle number per interface area, high ramp end force and high US power should be chosen. Below a threshold of 160 digits for the US power, the values are at a relatively low level, independent of the ramp end force. This parameter combination should therefore rather be avoided.

Also of some interest is the development of the interface shape for different bond parameter settings, which is described by the ratio of interface length to interface width. The corresponding graph shows that US power has considerable influence on whether the interface surface is more round (ratio close to 1) or elliptical (see Figure 4). The choice of the Ramp End Force is not decisive for the interface shape. If an approximately elliptical shape is to be achieved, a maximum US power of approx. 140 digits may be selected for the investigated process. This leads to a ratio of approx. 1.7-1.8 with a ramp end force of approx. 800 cN.

Summary:

Which conclusions can be drawn from the study presented? First, it becomes clear that by using the BAMFIT method a much more detailed analysis of the bond interface or the areas connected during bonding is possible. Furthermore BAMFIT provides a measurement value that reflects the number of mechanical cycles the bonding contact can withstand at a given load. This allows a quantification of the bonded area and thus a direct conclusion on the bond quality. In addition, a form factor can be determined which provides information on whether the interface is rather round or elliptically shaped. When comparing the shear forces and the BAMFIT cycle numbers, it is strikingly clear that for a specific bond parameter setting (US Power approx. 165 digits, Ramp End Force approx. 900 cN) a maximum shear force is predicted, while the BAMFIT cycle numbers keep increasing. This fact confirms the frequent observation that the shear test is influenced by the condition of the bond. If the wire material was very strongly deformed and softened by the acting ultrasound, the shear tool cuts through this region at a lower force. This means that only the wire material is mechanically tested and no longer the connection zone (interface). With the BAMFIT method, this effect is not seen in the selected test setup. The BAMFIT method therefore tests the state of the interface-related bond formation in any case, regardless of whether high or low bond parameter settings were used.

The BAMFIT method is intended to evaluate the reliability of a wire bond contact in Active Power Cycling at an accelerated rate. This fact still has to be confirmed by independent tests by the industry. If this fact is clearly confirmed, this application report shows that the test procedure can be seamlessly integrated into a DoE for process optimization.

The SpeedCycle project will evaluate the BAMFIT process for industrial use and extensively investigate the correlation between shear test and BAMFIT result.

Information about the SpeedCycle project:

www.bond-iq.de/speedcycle-english

Seminars about wire bonding, everything about process optimization and technology at:

www.bond-iq.de

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