Application Note 5SYA 2043-04

Load-cycling capability of HiPak IGBT modules

The HiPak power semiconductor modules are designed for reliable operation under demanding conditions throughout the module's lifetime. The operation conditions and thus the expected module's lifetime strongly depends on the application. In operation, the modules are subjected to a variety of temperature profiles, which cause cyclic thermo-mechanical stress in all components and joints of the modules and finally lead to device failure.

1. Introduction

The magnitude and frequency of these stress-cycles define the lifetime expectancy. Each specific profile leads to different stress distribution throughout the module, so that the weakest link of the module, which finally leads to failure, can be found in different components or joints. Moreover it is not possible to calculate the exact lifetime of individual modules. Instead the lifetime must be expressed in terms of the B_{10} lifetime, which is the number of cycles during which 10 percent of the total number of modules fails.

The aim of this application note is to provide load cycling lifetime data for the power electronics designer to estimate the module lifetime for optimisation of the particular application. Prior to this new application note version, the load cycling reliability of the HiPak power modules was described in the first version of this Application note. The lifetime data was given in two lifetime curves. One was for a slow cycle period (t_{cycle} = 2 min) and the other curve for a fast cycle (t_{cycle} = 2 s). These curves were valid for the whole power module including all components and joints.

Since the release of the first version of this application note, more power cycling data has become available and more sophisticated solder and wire bond fatigue models have been created. Therefore, the need to release this new, updated revision. Here, individual lifetime curves are presented for the critical joints, each of which fail due to different failure mechanisms [1, 2] and are described by different life time models. Moreover, for each critical joint several lifetime curves are calculated and plotted for different cycle periods (t_{cycle}) and the absolute temperatures (T_j or T_c). All these curves represent a wide matrix of accurate lifetime data under numerous cycling conditions.

2. Lifetime assessment

2.1. Power cycling experiments

The lifetime of the power modules is assessed by power cycling experiments, in which a given temperature cycle is repetitively applied to a module until it fails. The failure criterion is defined as a 5 % increase in V_{ce} or a 20 % increase in R_{th} of the tested module. The modules' temperature increases as current passes through the chips and they are cooled by the cooler mounted on the base plate. The temperature cycle is generally defined by the minimum and maximum values of the temperature and the period of the cycle. In order to complete the experiment within a reasonable period of time, the power modules are subjected to higher temperature swings than in a typical application.

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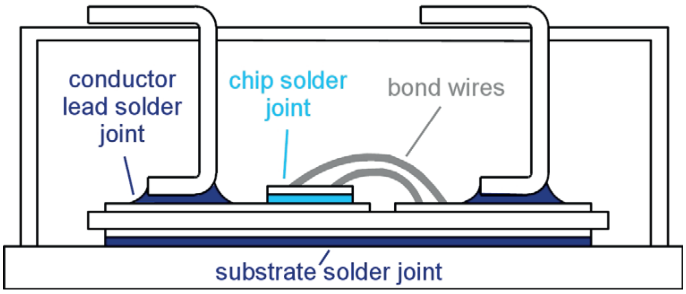
2.2. From experiments to lifetime models

The modules' lifetime is described using a two parameter Weibull distribution. The Weibull shape and scale parameters are fitted to the obtained lifetimes of the individual modules in the power cycling experiment. The resulting Weibull distribution is used to determine the B_{10} lifetime under the given cycling conditions.
In order to calculate the lifetime under different cycling conditions than in the power cycling experiment, lifetime models are required. The lifetime models in this application note are based on the Coffin-Manson law and fatigue of the joints due to plastic deformation [2-4]. Lifetime data from power cycling experiments and material creep data from the literature is used to build the lifetime models. Three different models describe the lifetime of the solder joint of the die attach (chip solder joint), the solder joints of the conductor leads and substrates, and the wire bonds, respectively. The different joints in a power module are depicted in figure 1.

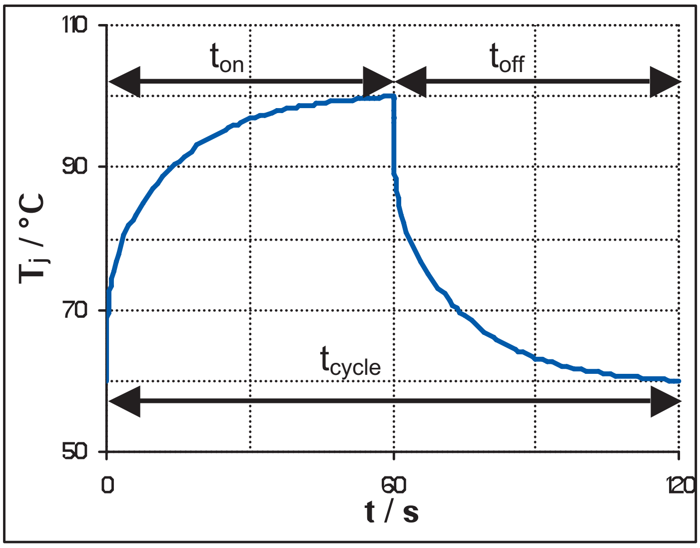


1 Sketch of the different joints in a power module

The lifetime models for the solder joints are based on time dependent creep and therefore the cycle period (t_{cycle}) has an influence on the solder joint lifetime. On the other hand the model for the wire bond lifetime is independent of t_{cycle}, because this model assumes that immediate plastic deformation leads to fatigue instead of time dependent creep.
An example for the temperature profiles used to calculate the fatigue per cycle in the solder joints is shown in figure 2. The example shows the temperature profile used for estimating the chip solder lifetime for t_{cycle} = 120 s, $T_{j,max}$ = 100 °C, and ΔT_j = 40 K. All the profiles for the solder joint lifetime estimation are of similar shape, despite the different cycling conditions.

2.3. Lifetime in terms of the B_{10} lifetime

The modules' reliability is defined by the B_{10} lifetime, which is described as the number of cycles where 10 % of the modules of a population fail [5]. The B_{10} lifetime curves are generated using the lifetime models and the temperature profile in figure 2.
Taking into account that the power modules are heated by the chips and cooled at the base plate, the length of the heating and cooling periods defines the level of the thermo-mechanical stress at each



2 Temperature profile for the lifetime calculation of the chip solder joint for t_{cycle} = 120 s, $T_{j,max}$= 100 °C, and ΔT_j = 40 K.

component or joint. In case of a short cycling period (e.g. t_{on} = t_{off} = 1 s) the chips and wire bonds are exposed to the temperature cycles while the case temperature (T_c) remains fairly constant. In addition the lifetime of the solder joints depends on tcycle as explained above. Therefore, individual B_{10} lifetime curves are generated for the different solder joints for several ton and T_c or T_j values in order to cover as many realistic cycling scenarios as possible.

3. The load-cycling capability of the HiPak power modules

3.1. Lifetime of the solder joints of the conductor leads and substrates

The lifetime of the solder joints connecting the conductor leads to the substrates and the substrates to the base plate is described by the same model. Both solder joints are shown in dark blue colour in figure 1. The graphs in figures 3-6 show the B_{10} lifetime curves of these joints at various values of ton and $T_{c,min}$. The B_{10} lifetime values are also listed in tables 1 and 2 for simpler access to the lifetime data.
If necessary, the B_5 and B_1 lifetimes, which are the total number of cycles during which 5 % and 1 % of the modules' population fails, under the given cycling conditions can be calculated by multiplying the B_{10} lifetime with the factors k_5 = 0.90 and k_1 = 0.70, respectively. For example, it can be read from table 1 that the B_{10} lifetime is equal to 108'000 cycles for t_{cycle} = 10 s, $T_{c,min}$ = 40 °C, and ΔT_c = 60 K. The respective B_5 and B_1 lifetimes under these cycling conditions can be calculated as 95'400 and 74'200 cycles, respectively.

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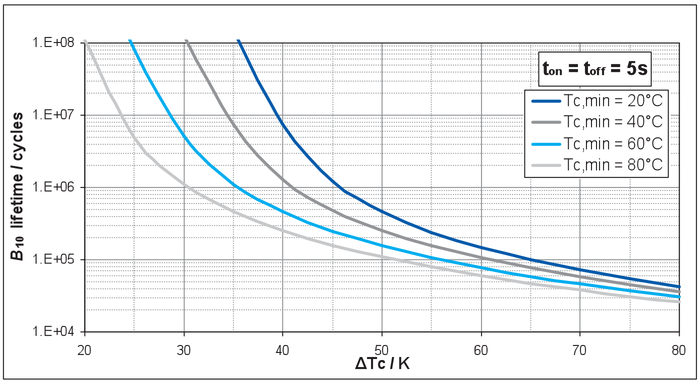
		ΔT_c [K]						
t_{cycle}	$T_{c,min}$ [°C]	20	30	40	50	60	70	80
10 s	20	> 10^9	> 10^9	7’000’000	473’000	150’000	72’900	43’200
	40	> 10^9	104’000’000	1’320’000	261’000	108’000	58’700	36’900
	60	> 10^9	5’150’000	470’000	159’000	78’600	46’900	31’100
	80	96’600’000	1’120’000	257’000	110’000	60’900	38’600	26’600
30 s	20	> 10^9	375’000’000	1’860’000	294’000	114’000	60’700	37’700
	40	> 10^9	13’400’000	625’000	183’000	86’100	49’900	32’600
	60	276’000’000	1’590’000	298’000	121’000	65’100	40’600	27’700
	80	13’700’000	636’000	192’000	91’200	52’900	34’500	24’300
120 s	20	> 10^9	4’680’000	402’000	138’000	69’500	42’000	28’200
	40	89’400’000	984’000	228’000	99’400	55’600	35’600	24’700
	60	5’110’000	446’000	153’000	76’500	45’900	30’600	21’900
	80	1’580’000	295’000	120’000	64’700	40’400	27’700	20’100

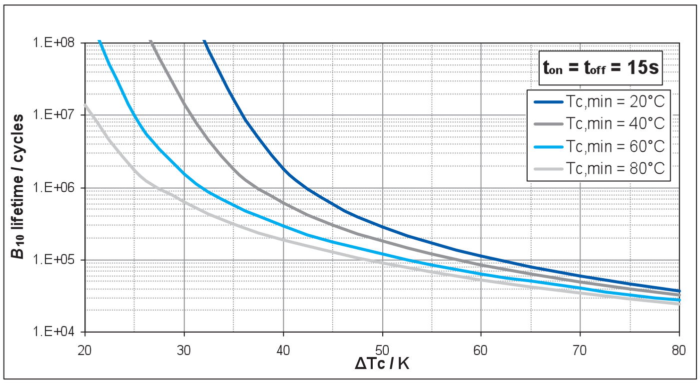
Table 1: The B_{10} lifetime data of the solder joints of the conductor leads and substrates at various tcycle, T_c, min, and ΔT_c values

	ΔT_c [K]				
$T_{c,min}$ [°C]	40	60	80	100	120
-20	156’000	44’700	21’200	12’400	8’190
0	120’000	39’600	19’700	11’800	7’860
20	94’400	34’800	18’100	11’100	7’470

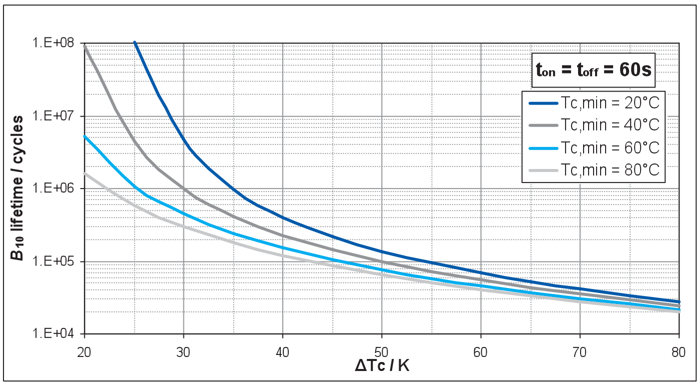
Table 2: The B_{10} lifetime data of the solder joints of the conductor leads and substrates for the daily cycles



3 The B_{10} lifetime curves of the solder joints of the conductor leads and substrates for t_{cycle} equal to 10 s



4 The B_{10} lifetime curves of the solder joints of the conductor leads and substrates for t_{cycle} equal to 30 s



5 The B_{10} lifetime curves of the solder joints of the conductor leads and substrates for t_{cycle} equal to 120 s

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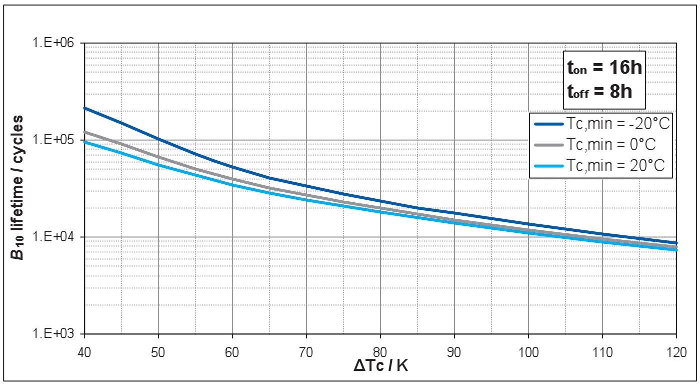
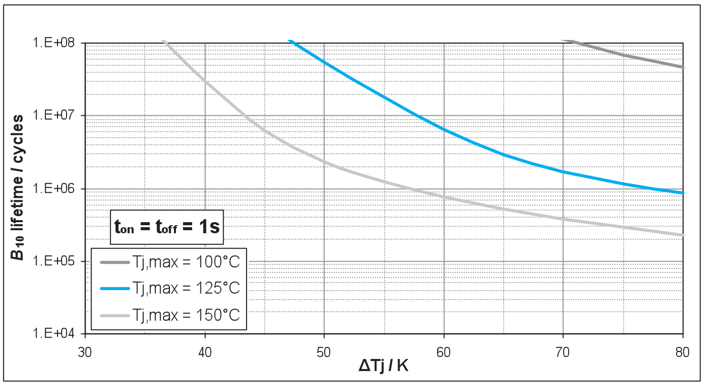


6 The B_{10} lifetime curves of the solder joints of the conductor leads and substrates for t_{cycle} equal to 24 h



7 The B_{10} lifetime curves of the solder joint of the chips for tcycle equal to 2 s

		ΔT_j [K]					
t_{cycle}	$T_{j,max}$ [°C]	30	40	50	60	70	80
2 s	100	> 10^9	> 10^9	981'000'000	180'000'000	54'600'000	24'600'000
	125	> 10^9	351'000'000	29'200'000	5'380'000	1'880'000	961'000
	150	667'000'000	19'100'000	2'580'000	874'000	441'000	272'000
10 s	100	> 10^9	328'000'000	31'400'000	6'620'000	2'500'000	1'380'000
	125	365'000'000	12'500'000	2'100'000	795'000	427'000	275'000
	150	23'200'000	2'130'000	700'000	348'000	211'000	143'000
30 s	75	> 10^9	> 10^9	249'000'000	55'600'000	21'300'000	12'100'000
	100	> 10^9	44'800'000	5'410'000	1'650'000	813'000	514'000
	125	50'700'000	3'310'000	948'000	449'000	267'000	182'000
	150	5'960'000	1'130'000	462'000	252'000	160'000	112'000
120 s	75	760'000'000	31'500'000	5'020'000	1'830'000	1'030'000	757'00
	100	19'300'000	2'110'000	731'000	379'000	241'000	173'000
	125	2'990'000	779'000	356'000	206'000	136'000	98'700
	150	1'370'000	482'000	245'000	149'000	101'000	73'600

Table 3: The B_{10} lifetime data of the solder joint of the chips at various t_{cycle}, $T_{j,max}$, and ΔT_j values

	ΔT_j [K]				
$T_{j,min}$ [°C]	40	60	80	100	120
-20	3'350'000	240'000	81'800	41'400	25'100
0	710'000	143'000	60'600	33'600	21'400
20	393'000	110'000	51'500	29'900	16'500

Table 4: The B_{10} lifetime data of the solder joint of the chips for the daily cycles

3.2. Lifetime of the solder joint of the chips

The lifetime of the solder joint of the chips is evaluated separately. The graphs in figures 7-11 show the B_{10} lifetime curves at various t_{on} and $T_{j,max}$ values. The B_{10} lifetime data is also shown in tables 3 and 4.

In figures 7 and 8, the lifetime curves for $T_{j,max}$ = 75 °C are not included because the B_{10} lifetime curves are above 10^8 cycles.

As the ton increases, the creep fatigue per cycle also increases. As a result, the B_{10} lifetime values decrease and the curve for $T_{j,max}$ = 75 °C appears in the graphs of figures 9 -10. The graph of figure 11 shows the expected lifetime for daily cycles.

If necessary the B_5 and B_1 lifetimes can be calculated by multiplying the B_{10} lifetime with the factors k_5 = 0.90 and k_1 = 0.70, respectively.

3.3. Lifetime of the wire bonds

The B_{10} lifetime curves of the wire bonds for various temperature profiles are shown in figure 12. The graph shows lifetime curves for varying $T_{j,max}$ values. The curves are based on the assumption that plastic strain leads to fatigue. The underlying model is fitted to large number of experimental data points at various cycling conditions. The B_{10} lifetime data of the wire bonds is also shown in table 5.

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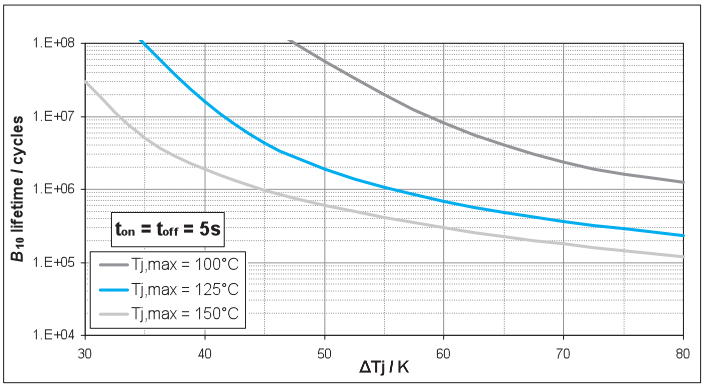
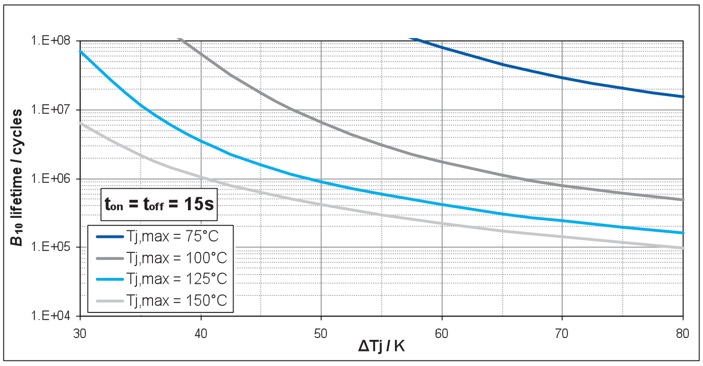
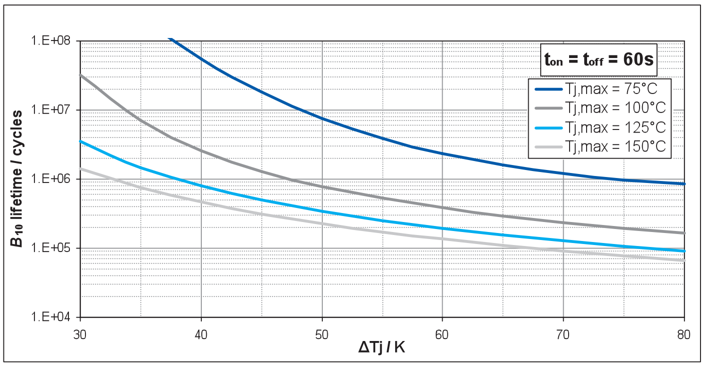


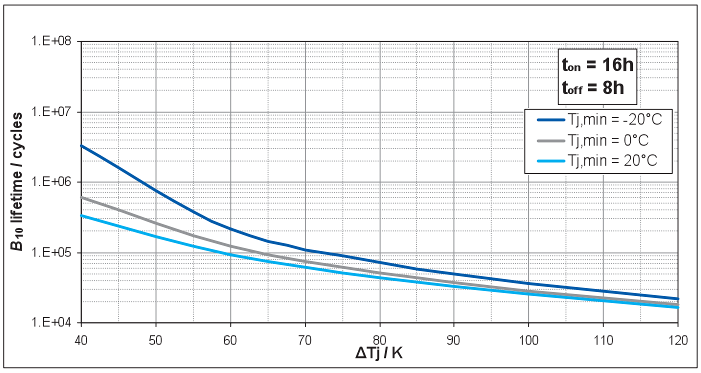
8 The B_{10} lifetime curves of the solder joint of the chips for tcycleequal to 10 s



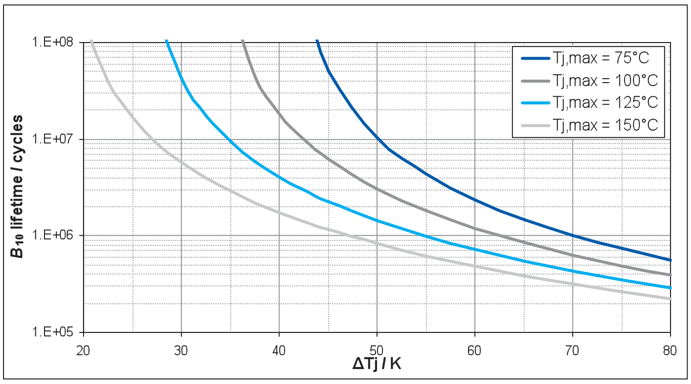
9 The B_{10} lifetime curves of the solder joint of the chips for tcycle equal to 30 s



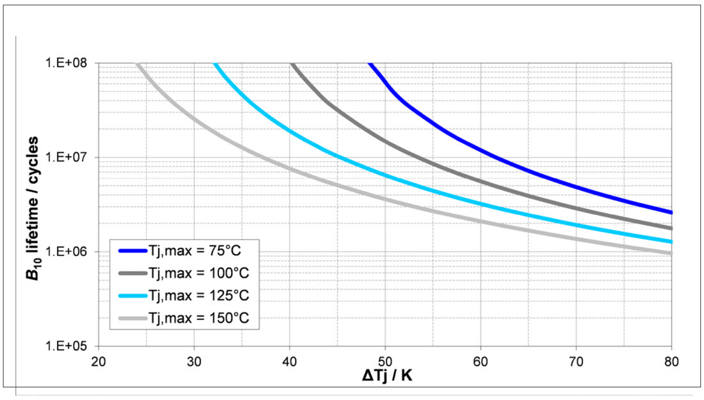
10 The B_{10} lifetime curves of the solder joint of the chips for tcycle equal to 120 s



11 The B_{10} lifetime curves of the solder joint of the chips for tcycle equal to 24 h



12 The B_{10} lifetime curves of the wire bonds for various cycling conditions valid for the classic HiPak modules (with epoxy filling)



13 The B_{10} lifetime curves of the wire bonds for various cycling conditions valid for the improved HiPak platform (epoxy-less)

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	ΔT_j [K]								
$T_{j,max}$ [°C]	20	30	40	50	60	70	80	90	100
75	> 10^9	> 10^9	> 10^9	10’300’000	2’350’000	1’010’000	560’000	355’000	245’000
80	> 10^9	> 10^9	> 10^9	7’560’000	2’010’000	912’000	518’000	334’000	233’000
90	> 10^9	> 10^9	61’900’000	4’550’000	1’520’000	753’000	448’000	297’000	211’000
100	> 10^9	> 10^9	18’500’000	3’030’000	1’190’000	632’000	391’000	265’000	192’000
110	> 10^9	> 10^9	8’770’000	2’170’000	959’000	538’000	344’000	239’000	175’000
120	> 10^9	97’700’000	5’100’000	1’620’000	788’000	464’000	305’000	216’000	161’000
125	> 10^9	42’300’000	4’070’000	1’430’000	719’000	432’000	288’000	206’000	154’000
130	> 10^9	23’500’000	3’330’000	1’260’000	659’000	404’000	273’000	196’000	148’000
140	> 10^9	10’300’000	2’340’000	1’010’000	560’000	355’000	245’000	179’000	137’000
150	177’000’000	5’750’000	1’740’000	826’000	481’000	314’000	221’000	164’000	127’000
160	30’700’000	3’670’000	1’340’000	688’000	418’000	280’000	201’000	151’000	118’000
170	12’300’000	2’540’000	1’060’000	582’000	366’000	251’000	183’000	139’000	110’000
180	6’540’000	1’860’000	866’000	499’000	324’000	227’000	168’000	129’000	102’000

Table 5: The B_{10} lifetime data of the wire bonds at various $T_{j,max}$, and ΔT_j values valid for the classic HiPak modules (with epoxy filling)

The curves in figure 12 and the B_{10} lifetime data in table 5 are valid for the classic HiPak modules that can be recognised by the epoxy filling. The B_{10} lifetime curves and data of the improved HiPak module platform are given in figure 13 and table 6. The better performance of the improved HiPak comes from an optimised bond-layout and process parameters [6]. The modules of the improved HiPak platform can be recognised by the epoxy-less housing design, e.g. 5SNA 1500E330305 or 5SND 0500N330300 [6].
To calculate the B_5 and B_1 lifetimes, the B_{10} lifetime (figures 12 and 13, tables 5 and 6) should be multiplied by the factors k_5 = 0.82 and k_1 = 0.52, respectively.

4. Lifetime calculation of a traction application example

The following fictive example clarifies how to interpret the information in the given B_{10} lifetime curves and tables to estimate the lifetime of the power modules under certain conditions.
Let’s imagine a commuter train as an example for the traction application with the given temperature profile in figure 14 for the station to station cycles.

	ΔT_j [K]								
$T_{j,max}$ [°C]	20	30	40	50	60	70	80	90	100
75	> 10^9	> 10^9	> 10^9	62’600’000	11’900’000	4’840’000	2’610’000	1’630’000	1’120’000
80	> 10^9	> 10^9	> 10^9	42’700’000	9’940’000	4’320’000	2’400’000	1’530’000	1’060’000
90	> 10^9	> 10^9	557’000’000	23’500’000	7’290’000	3’500’000	2’050’000	1’340’000	949’000
100	> 10^9	> 10^9	109’000’000	14’800’000	5’570’000	2’890’000	1’770’000	1’190’000	858’000
110	> 10^9	> 10^9	45’000’000	10’200’000	4’390’000	2’430’000	1’540’000	1’060’000	779’000
120	> 10^9	683’000’000	24’400’000	7’450’000	3’560’000	2’070’000	1’360’000	957’000	710’000
125	> 10^9	237’000’000	19’100’000	6’480’000	3’220’000	1’920’000	1’280’000	909’000	679’000
130	> 10^9	119’000’000	15’300’000	5’680’000	2’940’000	1’790’000	1’200’000	864’000	651’000
140	> 10^9	47’600’000	10’500’000	4’470’000	2’460’000	1’560’000	1’070’000	784’000	598’000
150	856’000’000	25’500’000	7’620’000	3’610’000	2’100’000	1’370’000	964’000	715’000	552’000
160	131’000’000	15’800’000	5’790’000	2’980’000	1’810’000	1’210’000	871’000	655’000	510’000
170	50’400’000	10’800’000	4’550’000	2’500’000	1’570’000	1’080’000	790’000	602’000	474’000
180	26’500’000	7’800’000	3’670’000	2’120’000	1’380’000	972’000	720’000	555’000	441’000

Table 6: The B10 lifetime data of the wire bonds at various $T_{j,max}$ and ΔT_j values valid for the improved HiPak platform (epoxy-less)

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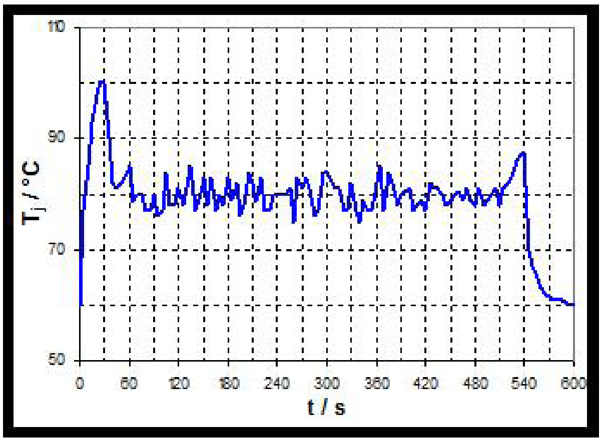
The following assumptions can be made:
- 16 hour operation per day
- 10 stops per hour (station to station cycles)
- Station to station cycles:
    - T_j: 60 °C (station) to 100 °C (during acceleration)
    - T_c: 60 °C (station) to 80 °C (during acceleration)
    - Acceleration period with max. load is 30 s
- Daily cycles:
    - T_j: 0 °C to 80 °C (average T_j during operation)
    - T_c: 0 °C to 70 °C (average T_c during operation)

The station to station cycle is roughly described by a rise to the maximum temperature during the acceleration phase of 30 s. The temperature decreases in the following 570 s to the cooling water temperature. For exactly this asymmetric cycle no lifetime data is available in section 3. The closest matching conditions for which lifetime data is given is $t_{on} = t_{off} = 60$ s. Therefore the corresponding load cycling lifetime data for the solder joints can be read from figures 5 and 10 as well as tables 1 and 3. Similarly, the lifetime data for the daily cycles can be read from figures 6 and 11 as well as from tables 2 and 4.
The wire bond lifetime data, which is independent of t_{cycle}, can be obtained either from figure 12 or table 5 for both station to station and daily cycles (valid for the HiPak modules with old epoxy design). The B_{10} lifetimes of the three different joints under the given conditions are summarised in table 7.



14 The temperature profile of the station to station cycle of the fictive example for a typical traction application.

	Station to station	Daily
Solder joints of conductor leads and substrates	5’110’000	27’000
Solder joint of the chips	2’110’000	60’600
Wire bonds	18’500’000	550’000

Table 7: The B_{10} lifetimes of the three different joints for station to station and daily cycles.

The annual consumption of the B_{10} lifetime can be calculated by dividing the number of cycles per year by the B_{10} lifetimes in table 7. The total annual consumption is the summation of the consumption due to the station to station and daily cycles according to the Miner’s rule [5]. The reciprocal of the total annual consumption defines the B_{10} lifetime in units of years.
For example, the modules are subject to 58’400 station to station and 365 daily cycles per year. In the case of the solder joints of the conductor leads, the annual consumption caused by the station to station and daily cycles is 1.14 % (= 58’400/5’110’000) and 1.35 % (= 365/27’000), respectively. The total annual consumption is 2.49 %, which results in a B_{10} lifetime of 40.2 years (= 1/2.49 %). Table 8 lists the annual consumption of the three joints and the resulting B_{10} lifetime in years for the given B_{10} lifetimes in table 7. The values were calculated as explained in the previous paragraph.

	Solder joint of conductor leads	Solder joint of the chips	Wire bonds
Annual lifetime consumption due station to to station cycles	1.14 %	2.76 %	0.32 %
Annual lifetime consumption due to daily cycles	1.35 %	0.60 %	0.07 %
Total annual lifetime consumption	2.49 %	3.36 %	0.39 %
B_{10} lifetime in years	40	30	256

Table 8: The annual lifetime consumption and B_{10} lifetimes of the different joint for the given traction example.

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5. References

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[5] B. Bertsche, “Reliability in automotive and mechanical engineering”, ISBN 978-3 540-33969-4.
[6] G. Pâques, et al. “A new HiPak module platform with improved reliability” (to be published), Proc. PCIM Europe 2014, Nuremberg, Germany.

6. Revision history

Version	Change	Authors
01		Nando Kaminski
02	Update of text and graphs	Emre Özkol, Samuel Hartmann, Hamit Duran
03	Improved numerical accuracy	Emre Özkol, Samuel Hartmann, Hamit Duran
04	B_{10} lifetime data of the improved HiPak platform	Emre Özkol, Samuel Hartmann

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