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Lifetime Analysis of Electronics and Power Electronic Components in Electric Vehicles

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Summary

Lifetime is one of the major quality measures in the automotive industry. For optimizing the costs, nearly all the vehicle components are designed to survive a certain time and usage. Over the last decades, this has been optimized perfectly. In the transition to the electric vehicles, many parameters do change now. In this paper we discuss not only the lifetime of the new power electronics, but we also review the vehicle requirements, since both, driving and charging do affect the component's lifetime – but quite differently.

Keywords: BEV (battery electric vehicle), charging, electric drive, inverter, reliability

1 Introduction

Reliability is key and thus lifetime requirements are an essential part of the automotive development process. Often, additional lifetime can be associated with additional costs. Just in rare cases, a component exchange can be accepted but requires then a maintenance strategy. For electronics and for power electronic components, this seems not to be acceptable. An electric vehicle (EV) does not only introduce new components but also new use cases, so the topic lifetime must be reevaluated.

Power electronic converters in electric vehicles, such as inverters, DC/DC converters and on-board chargers, have in principle two different kinds of active elements: On the one hand the high voltage path comprising of semiconductors, diodes and passive elements such as capacitors, coils and the contacting layers, being stressed by high currents and thus must overcome the related thermal stress. On the other hand, the low voltage control, e.g. the microcontroller and the other parts on the printed circuit board (PCB) have also to meet the lifetime expectations. Especially the high voltage components depend strongly on the vehicle usage profile which we must consider.

In this paper the vehicle usage profiles are discussed. As will be seen, the classical 8 000 h active hours of a vehicle with internal combustion engine (ICE) cannot be simply transposed to an electric vehicle. For instance, the behavior in idle mode is different and the cranking vanished. In addition, during charging, the vehicle is active for many additional hours. In chapter 2 we are going to discuss the vehicle's lifetime requirements to derive a reasonable specification of the new components. In chapter 3 we dive into the lifetime modelling of a power electronic component and its single elements. Finally, in chapter 4 we will discuss the results in comparison to car manufacturer's requirements.

2 Vehicle lifetime requirements

2.1 Former requirements for ICE vehicles

Each car manufacturer has its own set of lifetime requirements, which are specified as several thousand working hours and some hundred thousand kilometers. For passenger cars they vary as shown in Table 1. As a conservative set, we can assume here 8 000 h and 300 000 km. This corresponds to an average vehicle velocity of 37.5 km/h. Within these profiles, it is accepted to replace tires and brakes, but not belts and chains or even sparks. Moreover, no electronic control unit (ECU) or sensor should be replaced in that lifetime.

Table 1: Traction requirements from car manufacturers (bold: worst case)

Range [km]	Driving time [h]	Average speed [km/h]	Lifetime [y]	Yearly Mileage [km]
300 000	**8 000**	**37.5**	**15**	**20 000**
240 000	7 000	34.3	15	16 000
...	…	…	…	…

The total number of mileage and working hours is not sufficient to specify the component lifetime consumption. Important is the load collective, i.e. under which condition does the vehicle reach the total working hours and range. Table 2 shows a load collective example of different driving cycles. This is typically a collection of "standard" mission profiles like the WLTC or US cycles as well as OEM specific e.g. measured mission profiles. In addition to meet real vehicle life, hilly driving cycles and acceleration runs are included.

Table 2: Typical load collective requirement from car manufactures

Mission Profile	Duration [s]	Average speed [km/h]	Number of repetitions	Overall distribution [%]
WLTC	1800	46.5	2020	15
Artemis Urban	993	17.65	1815	8
US Highway	775	76.51	200	0.7
OEM city 1	1740	61	419	4
OEM hilly road	1236	36	872	12
OEM cycle…	…	…	…	…
Acceleration (0...80km/h)	48	38.49	2000	0.4
Acceleration (80...120km/h)	27	99.07	1000	0.12
Total				**100%**

For the component life time the distribution of these profiles is very important, i.e. the distribution of city, urban, highway driving and special cases like slopes (e.g. hill-hold) and acceleration driving.

When an ICE vehicle is used, and the car reaches a red traffic light, the engine runs in idle mode, means being active without need. The modern solution of start-stop systems tries to overcome this, mainly driven by emission targets. But unfortunately, this increased the number of cranking events dramatically, having its issues with the component reliability. So, components like the two-mass flywheel, belts and other mechanical parts influenced by the cranking where challenged by the field test of start-stop. Furthermore, modern features, like keyless entry and a monitoring system of the 12 V battery need to be active all the time when parked, which is by far not covered by 8 000 h of driving.

2.2 Lifetime requirements of an electric vehicle

The first approach for the lifetime requirements of an EV should be the same as the ICE vehicle as the EV should be able to substitute the latter. The first guess is then to neglect the red traffic light idle mode, because the e-machine does not rotate. However, for power electronics, this could be an active mode, e.g. in case of the hill-hold function. And even if not, the microcontroller and low-voltage components will be still awake. On top the vehicle is active while being charged. But what does that mean? A very misleading approach would be a gross charging time estimation like: It is charging on every whole night. Assuming here about 7h per night, this would lead to additional 40 000 h in 15 years which is not realistic. A more precise approach would be as follows: Charging with 3.7kW (16A @ 230V) corresponds to a *charging speed* of 20 km/h when assuming a driving consumption of ~180Wh/km. The term *charging speed* is an intuitive way to describe the gained range in km/h which is directly comparable with the energy consumption via the average driving speed. Based on that conversion factor, one could easily derive charging times for typical charging profiles. Table 3 gives a typical European mixed charging profile resulting in 9 313 h for 300 000 km (in [1], even less charging time was calculated), Table 4 gives a 100% Japanese home charger profile resulting in 8 400 h. Means, another 8 000 h to 10 000 h charging time need to be assumed.

Table 3: Charging profile 1 (e.g. European Mix Charger) with a total charging time of 9 313 h

	Charging Power [kW]	Occurrence [%]	Charging speed [km/h]	Charging time [h]
Home	3.7	50	20	7 500
Work	11	25	60	1 250
Public	22	20	120	500
DC	≥50	5	≥240	≤62.5

Table 4: Charging profile 2 (e.g. Japanese Home Charger) with a total charging time of 8 400 h

	Charging Power [kW]	Occurrence [%]	Charging speed [km/h]	Charging time [h]
Anywhere	6.6	100	35.7	8 400

In case of an architecture with an on-board charger (OBC), either the drivetrain or the OBC needs to be active. In case of a drivetrain with an integrated charging [2] [1], this gives up to 18 000 h maximum for both, driving and charging. But this does not mean to double the lifetime requirements of all components, as we will see in the following chapter, especially section 3.2.

3 Lifetime calculation of electronics and power electronics

With increasing car manufacturer demand for reliability data in an early design phase, it is necessary to analytically determine the applicable parts for lifetime analysis. This is because the Design Validation (DV) and Product Validation (PV) results or field data are often not yet available at this point of time. The following sections in this chapter show exemplarily how this is done for electronics and power electronic components.

Basically, a component failure rate can be described via the Weibull failure rate

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \tag{1}$$

With $\eta > 0$, $-\infty < \gamma < \infty$ and $t \geq \max(0;\gamma)$ describing a bathtub curve in three phases: The early *phase I* with $\beta < 1$ describes early failures and show a decreasing failure rate over time , the *phase II* with $\beta = 1$ show a constant failure rate over time, mainly caused by random failures. The *phase III* with $\beta > 1$ show a rising failure rate [3] (see Fig. 1).

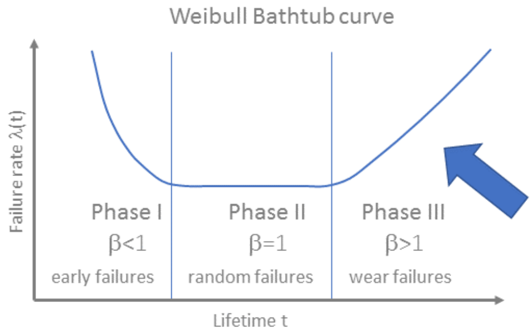

Figure 1 Weibull bathtub curve

In the following we are going to concentrate on the analysis of the *phase III* of the Weibull failure rate, since it is important to predict the end of life (EOL) failure rate.

3.1 Static qualification of Tier2 supplier parts

Looking on the physical effects, there is a huge variety of potential aging effects, different for each part and its environment. Starting with pure temperature dependencies following the law of *Servante Arrhenius* (1859-1927) to derive a possible failure time to more complex scenarios, wherein also voltage and current plays a role. A good summary of such effects can be found in [4].

A more practical approach for the industrial usage is described in the IEC 61709:2017 [5], providing a framework to relate given reference conditions with required operation conditions: Basically, the component failure rate λ can be described as

$$\lambda = \lambda_{ref} \times \pi_U \times \pi_I \times \pi_T \times \pi_E \times \pi_S \times \pi_{ES} \tag{2}$$

where λ_{ref} is the failure rate under reference conditions, $\pi_{U,I,T}$ is the voltage, current and temperature dependence factor, π_E is the environmental application factor, π_S the switching rate dependence factor and π_{ES} the electrical stress dependence factor [5].

As already stated, failure rates can only be considered constant within *phase II* of the bathtub curve (see Fig. 1), within the so-called *useful lifetime*. Since the results of safety analyzes (e.g. *Failure Mode, Effects and Diagnostic Analysis*: FMEDA and *Quantitative Fault Tree Analysis*: Quant. FTA) are based on constant failure rates, it must therefore be ensured that the parts used remain within this *useful life* over the entire predicted operation time. Therefore, the analysis based on *wear times* makes sense. This failure rate λ can simply be translated into a failure time giving us following fundamental equation to analyze if the used electrical components stay within their *useful lifetime*:

$$t_t = t_{op} \times \Pi_x \tag{3}$$

It relates operational conditions t_{OP} with the necessary test time t_t using one or more stress factors Π_x. The computed test time t_t will then be compared to qualification stress test-time t_Q from [6]. If $t_t \le t_Q$ holds true this would be a PASS otherwise a FAIL, for the electrical component under investigation.

Exemplarily the temperature dependent stress factor π_T is given via the Arrhenius equation:

$$\pi_T = e^{\left[\frac{E_{\alpha 1}}{k_0}\left(\frac{1}{T_{ref}} - \frac{1}{T_{op}}\right)\right]} \tag{4}$$

with the activation energy $E_{\alpha 1}$, the Boltzmann constant k_0, the operation temperature T_{op} and the reference temperature T_{ref} in case, only one activation energy needs to be regarded. The voltage dependent stress factor π_U via following empirical model:

$$\pi_U = e^{\left[C_3\left(\left(\frac{U_{op}}{U_{rat}}\right)^{C_2} - \left(\frac{U_{ref}}{U_{rat}}\right)^{C_2}\right)\right]} \tag{5}$$

with the operating voltage U_{op}, the reference voltage U_{ref} and the rated voltage U_{rat} and two empirical constants C_2 and C_3.

The activation energy $E_{\alpha 1}$ can be interpreted as the minimal energy for the occurrence of a failure. It is different per component and failure mechanism. The same applies to the constants C_2 and C_3. Depending on the type of component, different sets of the described stress factors need to be regarded.

Looking to the elements used in our power electronics, these parts will be grouped into appropriate categories, in this way not every single component has to be analyzed. From the bill of materials (BOM) two main groups could be figured out: standard and special components. The standard components are further divided into the part categories shown in Table 5. The table further states the stress factors to be regarded following [5]:

Table 5: Relevant PI Factors of supplier parts [5]

Part Categories	U	I	T
Capacitors (C)	yes	-	yes
Resistors (R)	-	-	yes
Inductors (L)	-	-	yes
Integ. Semi-Cond. (IC)	yes	-	yes
Discrete Semi-Cond. (T)	yes	-	yes
Diodes (D)	-	-	yes
Optocoupler (OC)	-	-	yes

As it can be seen from Table 5, for our application, the only relevant stress factors are π_T for temperature and π_U for voltage. The parametrization for the given part classes are listed in the standard.

Special components, such as µC, ASICs, Digital Isolators and DC Link Capacitors should be investigated in conjunction with their respective Tier2 suppliers to verify if the IEC61709 parameters can be applied. Often they have specialized failure rate prediction models based on their field experience.

As an example we give here the calculation for a Multi Layer Ceramic Capacitor (MLCC): Let's assume a standard MLCC with the following technical parameters: Dielectric: X7R, Capacity: 100nF, Tolerance: 10%, Maximum Rated Voltage: 50V and Package: 0603. According to Table 5, the stress factors π_U for voltage and π_T for temperature can be used. Referring to Tables 37 and 39 in [5], we get $E_{\alpha 1} = 0.35\ eV$ for equation 4 resulting in $\pi_T = 0.094$ and $\left(\frac{U_{ref}}{U_{rat}}\right) = 0.5$, $C_2 = 1$ and $C_3 = 4$ and $U_{OP} = 3.3$V for equation 5 resulting in $\pi_U = 0.176$. Following Table 2 of AEC-Q200 [6], the test is done at $T_{ref} = 125°C$ and lasts t_{AECQ} = 1 000 h. In this example, we assume a mean operation temperature $T_{OP} = 50°C$, the capacitor is used only with 50% of its rated voltage (25V) and an operation time of $t_{OP} = 48\ 000\ h$ (e.g. 8 000 h driving, 40 000 h worst case charging). With all that information we can calculate the necessary test-time t_t to project the qualification test parameters to the operational conditions.

$$t_t = t_{OP} \times \pi_T \times \pi_U = 48\ 000\ h \times 0.094 \times 0.176 = 794\ h \tag{6}$$

In this example, the selected MLCC is qualified for the assumed mission profile, because its qualification time t_{AECQ} = 1 000 h at the Tier2 supplier was longer than the required test time of 794 h.

During the vehicle's lifetime the mission profiles are not as simple as given in our example above. To meet real use cases, the whole mission profiles from chapter 2 must be transposed into temperature profiles and regarded accordingly. This weighting method will be described in subsection 3.2 for π_T of an IGBT.

3.2 Dynamic qualification via system simulation

In the following we will discuss the lifetime analysis of the entire system by means of simulation. The knowledge of the individual components described above, as well as the expected mission profiles of the system, play a role here.

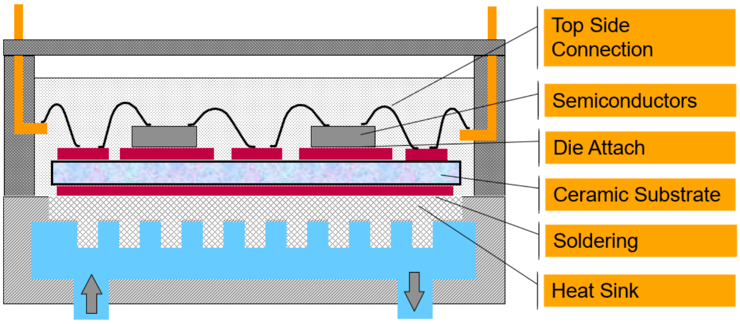

Figure 2: Cross-section of a power module with Si IGBT semiconductor switches and top side connection

Power electronic semiconductors (mainly IGBT, diode, or MOSFET) are considered as the most critical components in EVs. After a certain operation time, aging occurs which affects their reliability. For a precise prediction and potential defect avoidance, lifetime prediction under realistic operation conditions is crucial.

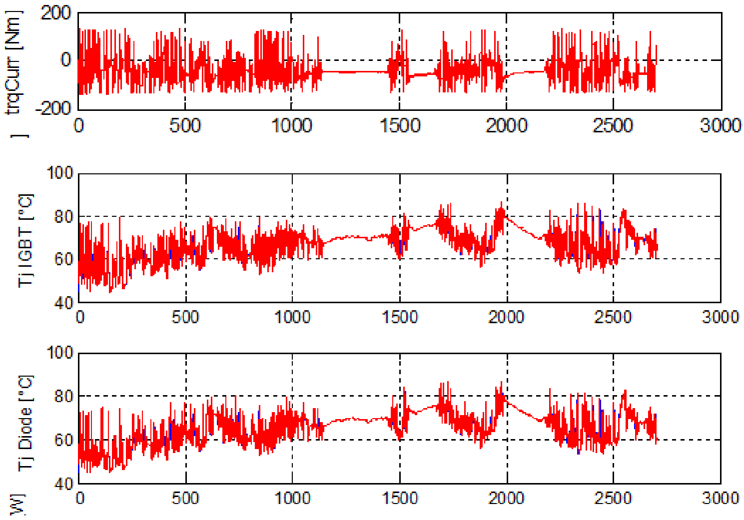

Figure 3: Exemplary mission profile applied (top) leads to the temperature stress for IGBT (middle) and Diode (below)

Power modules for automotive applications are commonly directly liquid cooled with a very straight thermal coupling between power semiconductor and coolant (see Fig. 2). Since this results in less thermal capacity, their thermal time constants are relatively low (typically below 1s). While driving a typical dynamic mission profile with many temperature swings on the semiconductors and the connections nearby are seen. This stresses the mechanical connections and results in aging of the components (see Fig. 3).

In contrast to the driving profile effect shown in Fig. 3, while charging the power semiconductors see a constant load and thus stay on a constant temperature. So, the aging of their interconnections is very small in this use case.

During working life, the question arises of how much influence a particular mission has on the lifespan of the component or system. Here we follow the laws of Palmgren-Miner, a simple cumulative damage model based on a linear damage hypothesis. Considering k different stress levels S_i, then one obtains after n_i cycles at this stress level a partial damage $W_i = n_i * S_i$, which one can set in relation to the failure $W_{i,Failure} = N_i * S_i$ after N_i cycles at this stress level. If you sum up the partial damage of all stress levels, you get:

$$\sum_{i=1}^{k} \frac{W_i}{W_{i,Failure}} = \sum_{i=1}^{k} \frac{n_i}{N_i} = C \qquad (7)$$

C is then the proportion of consumed lifetime, which reaches 0 when new and 1 at the end of life [7].

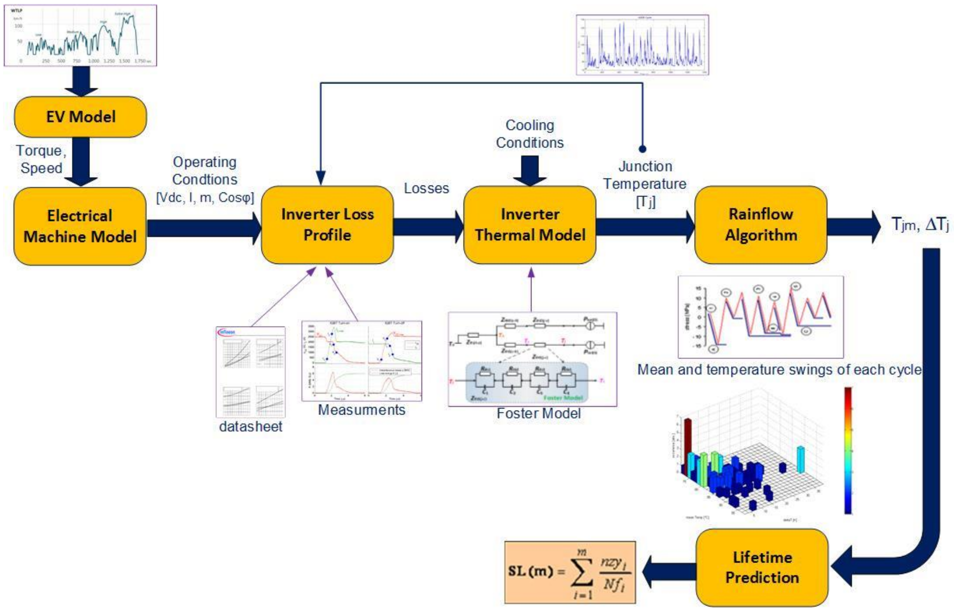

Figure 4: Lifetime analysis algorithm for power electronics in EVs

To simulate the lifetime of a power electronic device, certain steps have to be followed. The main steps are summarized in Fig. 4. It starts with the driving cycle, then followed by the electrical machine model that based on the DC-link voltage computes the required rms current, modulation factor, and power factor. These values are then input for the inverter model to calculate the losses of each switch and the total losses based on either datasheet information or experimental values. Using a thermal model (e.g. Foster model [8]) and considering the cooling conditions, the junction temperature of the switches is calculated. Fig. 4 further shows the step "Rainflow Algorithm", which is skipped for now and will be introduced in section 3.4. The resulting temperature profile of the IGBT is shown in Fig. 5.

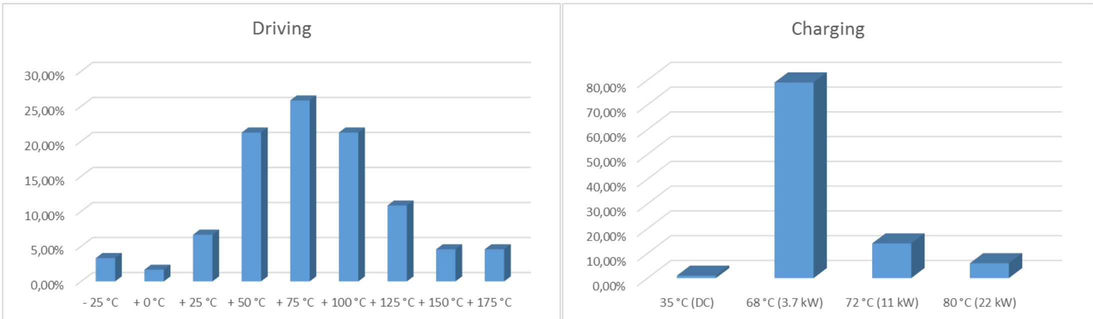

Figure 5: Temperature profile of an IGBT of traction inverter while driving (left) and diode while charging (right). The IGBT does not warm up as much during charging.

The left temperature profiles in Fig.5 is based on the driving profile shown in Table 2 used to derive a weighted π_T for driving (see Table 6). Based on this, a required test time for driving can be derived as:

$$t_{t,driving} = t_{OP} \times \pi_T = 8\,000h \times 0.0355 = 284h \quad (8)$$

The right temperature profile in Fig. 5 is based on the charging profile in Table 3 and used to derive a weighted π_T for charging (see Table 7). Based on this, a required test time for charging is:

$$t_{t,charging} = t_{OP} \times \pi_T = 10\,000h \times 0.0021 = 21h \quad (9)$$

Which is just 7.4% of the driving aging effect and just 2.1% of the component test time of 1000 h.

Table 6: Temperature dependent stress factor calculation for driving

Weight	IGBT Junction Temperature [°C]	weighted π_T
3.33%	-25	6.70085E-09
1.67%	0	6.70302E-0.8
6.67%	+25	3.24559E-06
21.25%	+50	8.51418E-05
25.83%	+75	0.000629358
21.25%	+100	0.002471535
10.83%	+125	0.004943162
4.58%	+150	0.006980948
4.58%	+175	0.02037037
	Total weighted π_T driving	**0,0355**

Table 7: Temperature dependent stress factor calculation for charging profile 1 (see Table 2)

Weight	IGBT Junction Temperature [°C]	weighted π_T
1%	+35	1.47326E-06
79%	+68	0.001490509
14%	+72	0.00034808
6%	+80	0.000254241
	Total weighted π_T charging	**0,0021**

These results showed that in case of charging via the traction inverter [2] the effect on the lifetime is quite minor. The first reason is that the charging power is considered as partial load operation for the inverter. Second, the power switches are loaded with a constant power, thus their interconnection aging is uncritical.

3.3 Integration, assembly and connection technology

The power electronic modules are manufactured in a multilayer structure (e.g. see Fig. 2). Each material undergoes an expansion depending on the temperature. The coefficients of thermal expansion (CTE) and thus the length expansion of different materials is different, therefore naturally arise at material joints mechanical stresses. These loads are an important cause of component failures and so their lifetimes. For example, the solder and the boundary between Al bonding and Si IGBT chips is very critical.

Simplified, such loads can be modeled as a sum of periodic loads, for example sinusoidal oscillations. Small (elastic) stress amplitudes are not critical, but higher amplitudes lead to plastic material deformations. The transition is fluent, even a high number of load cycles with a small amplitude can lead to a long-term failure. These effects affect the time stability, which can be statistically described by a Wöhler curve. In the low-cycle fatigue range (LCF), typically in the range of 10^0 to10^5 load cycles, the Wöhler curve can be described by the Coffin-Manson relationship [9]:

$$N_f = A * (\Delta\varepsilon)^{-B} \quad (10)$$

With the failure time N_f (fatigue life), the fatigue coefficient $\Delta\varepsilon$ (strain amplitude, corresponds to an infinitesimal deformation per cycle), the Coffin-Manson coefficient A (a material constant to be determined experimentally) and the material-dependent damage coefficient B (to be determined experimentally).

Performing lifetime analysis via field tests requires a lot of time. Therefore, one uses a method of standardized temperature cycling tests to shorten the test time. The Coffin & Manson parameters can be determined experimentally by comparing the lifetimes from temperature cycling tests with different test conditions.

For chip-based assembly and connection technology, active load change tests (power cycling) are carried out under different test conditions (temperature lift / medium temperature) until failure.

Fig. 6 shows an example of the results of two series of measurements with a temperature shock of 100K. The blue dots on the left show a sample of IGBTs soldered at the bottom side and bonded on top. The three straight lines show the mean distribution and the upper and lower confidence limits at 5% and 95%, respectively. The measurements showed a characteristic fatigue life $N_{f,char} = 94\,013$ cycles, which we define at 1% failure rate.

The red dots on the right show a selection of IGBTs connected via silver sinter technology on both sides. This resulted in $N_{f,char} = 1\,372\,267$ cycles, which is more than one order of magnitude above the other connection technology.

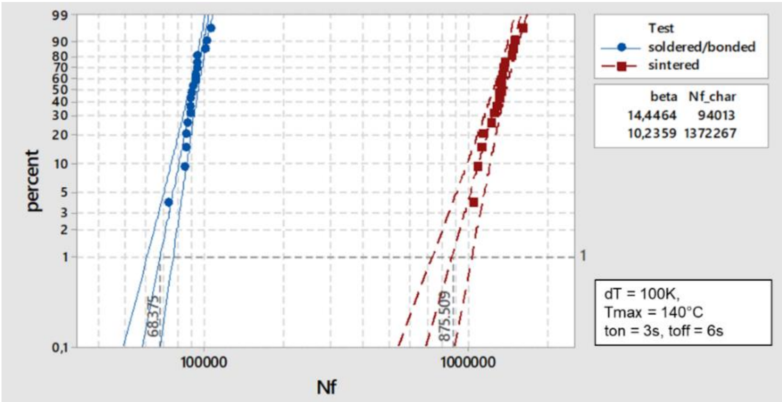

Figure 6: Exemplary comparison of soldered/bonded vs. sintered technology

The huge life difference can be explained as follows: Sold and Aluminum on the one hand and silver on the other hand have different CTEs and melting points. If the connection technology turns out to be the weak point, the semiconductor might be oversized in its lifetime budget. To harmonize the subcomponents more economically, therefore, a connection technology is needed that comes closer to the semiconductor's lifetime.

Based on these results one can now vary the technologies and/or process parameters to achieve target lifetime values in between these results. One obtains a degree of development freedom for the optimization with respect to lifetime (e.g. needed for commercial vehicles) and performance of the same semiconductor area while driving higher ΔT in the application.

In an electric vehicle, one currently assumes maximum coolant temperatures of approximately 65 °C – 70 °C. Due to the presence of the internal combustion engine in a hybrid vehicle, the coolant temperature may be 85 °C, depending on the packaging. The transition from the combustion mode to the EV mode at full performance can therefore have a critical influence on the service life and therefore on the choice of the connection technology used. A lifetime analysis of the component must therefore be carried out in the system context, as we will show in the next section.

3.4 System simulation of the assembly and connection technology

Two mechanisms contribute to the inverter temperature: Passive and active temperature changes. Passive temperature changes caused by components, which are connected to the inverter coolant system, e.g. the air conditioner or a passenger compartment heater. These components change the inverter coolant temperature and therefore the IGBT device temperature without any activities of the inverter component itself. However, the passive temperature changes cause lifetime consumption, which will be typically considered as a certain margin in the component design following equation 4.

The active temperature changes caused by the inverter (power module) itself through the usage of current. To consider only the effective temperature cycles, the Rain-Flow algorithm [10] is used. Out of this algorithm two important values are provided and used as input for the lifetime prediction in the system simulation: The mean junction temperature T_{jm} and the temperature range ΔT_j (see Fig. 4). The following examples will show the stress difference between three cycles with a certain vehicle, coolant temperature and battery voltage.

The first example is a "standard" urban mission profile (Fig. 7). The left plot shows the velocity profile and the right plot shows the inverter temperature distribution. The second example shows a vehicle full accelerator pedal profile (0…150 km/h) (Fig. 8). The third example shows the result for the WLTC (Fig. 9).

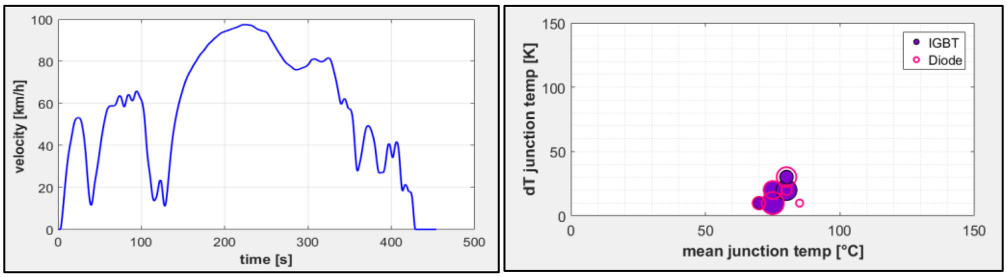

Figure 7: Urban mission profile and inverter temperature distribution

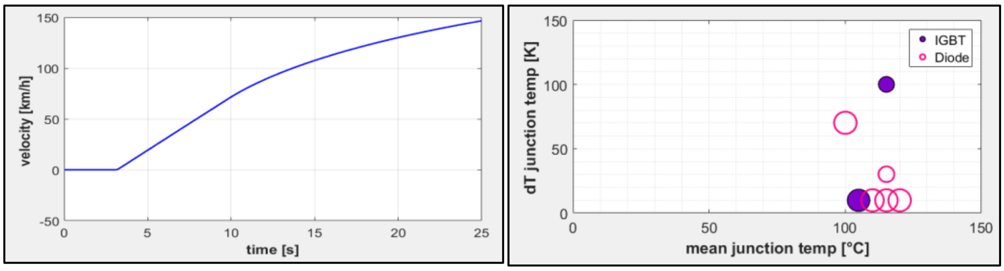

Figure 8: Full accelerator pedal mission profile and inverter temperature distribution

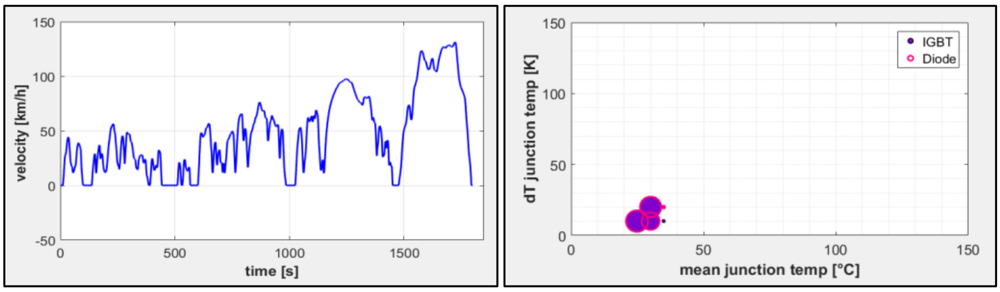

Figure 9: WLTC mission profile and inverter temperature distribution

Although the full accelerator pedal mission profile is much shorter in time than the urban driving profile, it can be seen, that the inverter temperature stress, and therefore the lifetime consumption is much higher in the full accelerator pedal mission profile.

The stress of the full accelerator pedal mission profile is higher in consideration of the mean junction temperature as well of the temperature range ΔT. As described above these both parameters finally define the assembly and connection technology and therefore also the component price.

In conclusion the selection and distribution of the mission profiles have a huge impact on connection technology and therefore the component costs.

4 Discussion

The automotive use cases show a huge variety, so a simple lifetime analysis like shown in section 3.1 could be sufficient but could fail also. For certain part categories (e.g. IC, FET), the AEC-Q defined test-times and temperatures sometimes do not cover the operational conditions. This must be handled twofold: Firstly, those Tier2 supplier tests just show a positive test and does not reveal the component's potential further lifetime. Secondly in real life, not all π factors appear on maximum at the same time. As rough indication for test parameters (e.g. for high temperature operational life test (HTOL)) when choosing electrical components, it can be mentioned that 1 000 h at 125 °C is often not sufficient to represent a vehicle lifetime, 1 000 h at 150 °C is borderline, a qualification at 2 000 h at 150 °C and 1 000 h at 175 °C would pass our requirements in most cases. More care needs to be taken for components with high self-heating caused by high power dissipation or a high thermal resistance of the package.

A proper and reliable choice can only be taken based on a system simulation of the vehicle's mission profiles, like shown in section 3.2. When focusing on straight thermal coupled components, such as IGBTs in a power module, the right connection technology needs to be selected properly. Thermal design considerations shall also encompass parts on the PCB, not only the power module, because part temperatures should be as low as possible to gain appropriate acceleration factors.

The analysis of sections 3.3 and 3.4 revealed the need of system analysis to choose the right connection technology: In cases the car manufacturer does not expect many situations leading to high junction temperatures and temperature changes, the cheap and established bond technology could be the right choice. On the other hand, the high performant sinter technology gives much higher lifetime and opens the door for different design criteria, such as less thermal coupling or smaller chips sizes.

Finally, we've seen that charging profiles do affect the lifetime much less than often expected in today's specifications. Furthermore, since this mode gives a constant load and thus a thermal equilibrium, rather than the thermal cycling while driving, one charging hour counts much less than one driving hour in lifetime. Finally, in case of a drivetrain integrated solution, each AC charging event runs just in partial load of the inverter and thus is even uncritical. This is beneficial for drivetrain integrated charging solutions, since this function costs just additional ~2% of the lifetime budget.

When looking into the car manufacturer's requirements of up to 40 000 h additional operating hours of electric vehicles, compared to classical ICE vehicles, we have several potential interpretations: Some may not have much experience with EVs and thus fear or misunderstand the charging part, some may foresee an unrealistic user charging only at 1.4 kW (7.5 km/h) during the whole vehicle lifetime. But maybe some have additional use cases in mind, such as using the car for different purposes and thus require more energy for comfort than just for driving. Probably this is also a hint towards bidirectional charging use cases, such as *vehicle-to-load* or *vehicle-to-grid*. If the additional 40 000 h for charging would become truth, one would need to analyze, if one could assume charging-like profiles or some with a bit more dynamic, but far from a driving profile. So, the additional functions of an EV will most likely not be lifetime critical. And this is a promising result for electric vehicles!

References

[1] M. Bruell und P. Brockerhoff, „Avoid the DC charging trap," in *Electric Vehicle Symposium EVS30*, Stuttgart, 2017.

[2] M. Bruell, P. Brockerhoff, F. Pfeilschifter, H.-P. Feustel und W. Hackmann, „Bidirectional Charge- and Traction-System," in *EVS29 Symposium*, Montréal, Québec, Canada, 2016.

[3] J. Juskowiak, Beanspruchungsgerechte Bestimmung des Weibull-Formparameters für Zuverlässigkeitsprognosen, Stuttgart: Institut für Maschinenelemente der Universität Stuttgart (ISBN 978-3-936100-74-7), 2017.

[4] A. Middendorf, Lebensdauerprognostik unter Berücksichtigung realer Belastungen am Beispiel von Bondverbindungen bei thermomechanischen Wechselbeanspruchungen, Dissertation: Technische Universität Berlin, 2010.

[5] IEC 61709 , Electric components - Reliability - Reference conditions for failure rates and stress models for conversion, International Electrotechnical Commission (IEC).

[6] AEC-Q200: Stress Test Qualification for Passive Components, Automotive Electronics Council, Rev D: 2010.

[7] „Miner's Rule and Cumulative Damage Models," ReliaSoft Corporation, [Online]. Available: https://www.weibull.com/hotwire/issue116/hottopics116.htm. [Zugriff am 29 01 2019].

[8] Infineon Technologies AG, „Transient Thermal Measurements and thermal equivalent circuit models," *AN 2015-10,* 2015.

[9] T. Hannach, Ermittlung von Lebensdauergleichungen vom Coffin-Manson- und Morrowtyp für bleihaltige und bleifreie Weichlote durch Kombination von FE und Experiment, Berlin: Technische Universität Berlin, 2017.

[10] G. Glinka und J. Kam, „Rainflow counting algorithm for very long stress histories," *International Journal of Fatigue,* Bd. 9, Nr. 3, pp. 223-228, Feb. 1987.

[11] M. Matsuishi und T. Endo, Fatigue of metals subjected to varying stress, Japan Soc. Mech. Engineering, 1968.

[12] Manca, J., W. Wondrak, K. Croes, W. De Ceuninck, V. Haeger und L. De Schepper, „The Arrhenius Relation for Electronics in Extreme Temperature," *IEEE,* pp. 29-32, 1999.

[13] AEC-Q100: Failure Mechanism Based Stress Test Qualification for Integrated Circuits, Automotive Electronics Council, Rev H: 2014.

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