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FEM-aided damage model calibration method for experimental results

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ABSTRACT

This paper presents a novel loading evaluation procedure to be used for IGBT power cycling. The method is a combination of experimental life tests and finite element analysis digital twin. It was validated and predicted the life-time with 2.77% error, compared to the 8.78% error of the reference.

1. Introduction

Before a power electronic product meant to last is released, accelerated life tests can be used to test the durability and reliability of a component in an accelerated time frame. For life-time testing of power electronic components, power cycling tests are the most common method used to evaluate the life-time of a component.

Accelerated life tests can be both lengthy and expensive and very often it is both necessary to test multiple test conditions and multiple samples at each test condition to be able to trust the statistics based on your results.

In this paper a new fitting procedure for empirical power cycling tests will be proposed, this method is based on finite element analysis digital twin modelling and offers an alternative loading factor to represent the life-time consumed for the tested loading conditions.

First the state of the art of life-time modelling methods will be reported. Then the new approach will be presented. The step by step methodology of the approach will be detailed through a case implementation. Finally the prediction results are presented and the work is concluded.

2. State of the art

Ref [1] offers a review of the state of the art for lifetime prediction of power electronics devices. The review reports a large number of empirical damage models and discusses degradation monitoring and power cycling methodology.

Currently the lifetime prediction for a power electronics component is based on experimental accelerated life tests and fitted to one of various lifetime models [2–6].

References [6, 7] detail various ways to perform time and resource costly damage modelling. Reference [7] reports a way to perform micro-structural damage modelling of the topside metallization of a silicon chip. The thermal fatigue of a solder joint is modelled in [6]. Here the damage of the solder layer in a power module is found on the solder grain level, yielding in an accurate model of the damaged grains in the solder layer.

When modelled on the bond-wire or solder layer grain level even a single power chip becomes very large in relation, and the simulation time and model calibration time become long.

Reference [8] shows, step by step, an approach to designing for reliability for power electronics. It reports some of the failure-mode physics and ways to reliability prediction.

Reference [3] uses a thermo-mechanical finite element model of a bond-wire to predict high-cycle fatigue. Here the simulated stress is used as the loading term in the Basquin equation, see Table I.

It can be difficult to choose a life model, not least because of the high number of models to choose between. The life models, of which a selection can be seen in Table I, are similar as they are all empirically fitted equations, but differ both in the loading quantity and the number of loading quantities.

Some of the functions consider the loading with mechanical terms, others look at the loading in thermal terms and some consider the duration of the cyclic loading. Reference [9] investigates different life testing strategies, and shows the importance of choosing the correct loading quantity, as different loading quantities are affected differently by different loading strategies.

This project was started with a wondering about the fact that life models usually only have one or few load terms and whether or not it was certain that the chosen loading term was optimal.

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Table I
Table of life models.

Name	Equation	Loading term(s)	Ref(s)
Coffin-Manson	$N_f = A(\Delta\varepsilon_{pl})^B$	$\Delta\varepsilon_{pl}$	[2]
Coffin-Manson (Temp)	$N_f = A(\Delta T_j)^B$	ΔT_j	[1]
Modified Coffin-Manson	$N_f = \frac{a + b(t_{\Delta T_j})^{-n}}{a+1}$	$t_{\Delta T_j}$	[11]
Modified Coffin-Manson	$N_f = A\Delta T_j^{-\alpha} exp\left(\frac{E_a}{k_B T_{jm}}\right)$	ΔT_j, E_a, T_{jm}	[4]
Basquin	$N_f = a(\Delta\sigma_e)^{-b}$	$\Delta\sigma_e$	[3]
Bayerer	$N_f = K(\Delta T_j)^{\beta_1} e^{\left(\frac{\beta_2}{Tj+273}\right)} t_{on}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6}$	ΔT_j, T_j, t_{on}	[5]

Usually when accelerated life tests are conducted for power electronics components only electrical and/or thermal quantities are known for the device under test, despite the fact that the damage evolution in the device is a mechanical effect. Reference [10] shows a method to accurately measure the degradation of a bond-wire by monitoring the electrical resistance across it and it's contact zones, however such accurate measurements cannot be performed on off-the-shelf parts without altering their structure such as removing the gel or the moulding.

Many of the mechanical quantities are impractical or impossible to measure for an off the shelf component, and thus a digital twin of this component can be used to measure otherwise unmeasurable quantities of the device.

3. New modelling approach

This paper presents an original approach to fill the gap between basic empirical fitting and costly microstructural damage modelling. The approach will provide a straight-forward method of reducing lifetime prediction error by providing a physics-based loading factor. The procedure of this method can be seen in Fig. 1.

a) 1. CALT

The first step in the proposed methodology consists of conventional accelerated life tests. Here the device under test (DUT) is subjected to accelerating loading conditions and the number of cycles to fail is recorded for each test condition.

b) 2. Digital Twin and Quantities

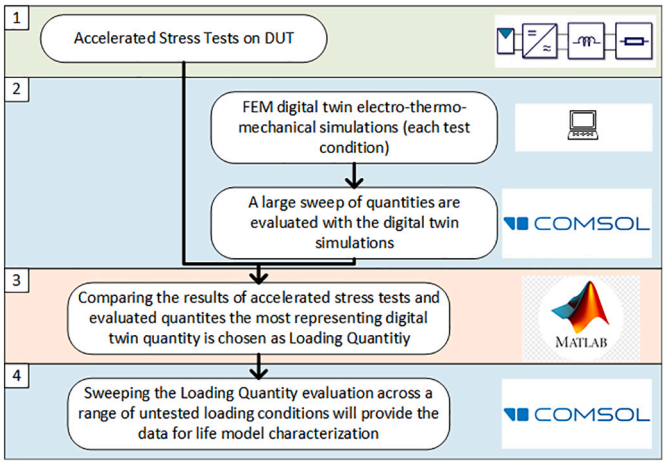


Fig. 1. Novel loading factor identification procedure for accelerated test by combining test and digital twin simulations.

A multi-physics digital twin of the component is set up in finite element modelling software, and is subjected to the same loading conditions as experienced by the module in the experimental accelerated life tests.

A range of physical quantities are extracted for each digital accelerated life test and evaluated in a range of different ways to create a large number of candidate loading factors for each test.

c) 3. Comparison and Fitting

Potential loading factors are analysed together with the experimental number of cycles to fail to find the best 'fit'. The loading factor candidate, which can best express the loading experienced by the physical DUT is used as the loading factor for continued analysis.

d) 4. Prediction using Chosen Loading Quantity

This loading factor and the relation of it to the number of cycles to fail can be used to predict the number of cycles to fail for new untested loading conditions.

4. Implementation for device

The procedure proposed in the previous section will be detailed in this section with an implementation example.

For the purpose of this example the DUT, test set-up and loading conditions are used from [11]. The module was set up with the relevant materials in a 3D thermo-mechanical modelling domain.

e) 1. CALT

The test conditions from [11] consist of repeated semi-sinusoidal junction temperature swings with different lengths for the different conditions. Thus the simulation was set up to replicate the same temperature swings. The reference [11] contains more information on the test conditions but Table II lists some of the main points and Fig. 2 shows the loading.

f) 2. Digital Twin and Quantities

As the relative loading of one test condition compared to the other was desired and not the loading of the degrading component during it's life, only one pulse or cycle of each loading cycle was simulated with the digital twin model. This also allows the simulation to be time efficient enough for practical analysis.

As the digital twin is intended to be a representation of a real component the geometrical structure of the physical device must be constructed in the software. In this example the device under test (DUT) is a moulded power module. The module was modelled from the case all in the way in to each semiconductor chip including the entire thermal stack and all bond-wires. The moulded case was also included as this will have a big impact on the mechanical behaviour of the geometry, especially the bond-wires.

The modelling software used in this study was COMSOL Multi-Physics.

Table II
Test conditions from [11].

Condition	ΔT	T_{max}	t_{on}
1	80.8[°C]	142.7[°C]	10[s]
2	80.6[°C]	142.8[°C]	5[s]
3	82.0[°C]	142.3[°C]	2[s]
4	81.6[°C]	142.3[°C]	1[s]
5	81.8[°C]	143.3[°C]	0.8[s]
6	80.8[°C]	142.4[°C]	0.59[s]

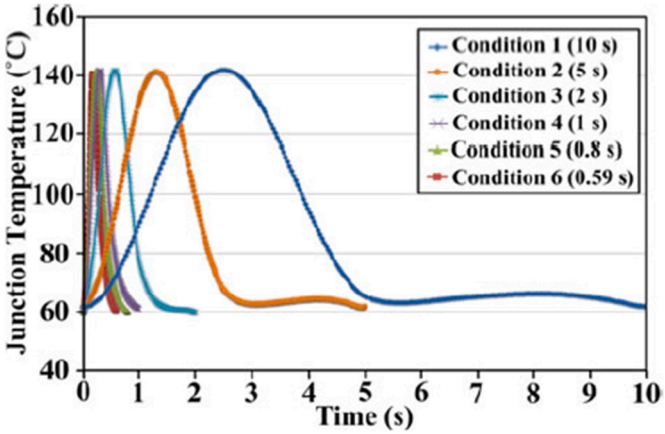


Fig. 2. Comparison of the loading of the different test conditions [11].

The multi-physics setting called "Thermal Stress" was chosen as it sets up the thermo-mechanical modelling. In the thermal domain the case temperature was set on the thermal interface at the underside of the module. Additionally heat was injected in the chips fitting with the losses experienced by the real device during the accelerated life tests. The multi-physics setting automatically imposes thermal expansion on the entire geometry so the last thing needed in the mechanical domain was the fixation of the module.

This model was used for simulation of the different loading conditions from Fig. 2.

The software offers a long range of quantities which can be evaluated over different parts of the geometry. These quantities represent different physical qualities of the model, e.g. the temperature at a specific point in the geometry. The chosen quantities are seen in the first column of Table III. The quantities were chosen from both the mechanical and thermal domains.

A number of steps were taken to reduce all of the information in the simulation of a loading cycle into a single scalar describing the loading.

These quantities were evaluated in three ways with regards to the geometry of the model. The quantities were evaluated for specific chosen points in the geometry (see Fig. 3c), and evaluated over/in the bond-wires (see Fig. 3b) and the entire module (see Fig. 3a). Notice that Fig. 3 shows only a cut-out of the geometry. These are also found in the second column in Table III.

The geometry selections from the previous were evaluated in various ways, these are found in column 3 in Table III. The physical quantities for a volume or part of the geometry was evaluated through either finding the maximum or integrating/summing the value of the volume.

Finally, as the loading and thus also the simulation was time-dependant the data needed to be reduced into a single scalar for the entire period. This way done, both by integrating the quantity during the period but also by looking at the maximum value or maximum $\frac{d}{dt}$. See the fourth column in Table III.

Table III
Overview of loading quantity evaluation methods.

Loading	Active area	Active area	Temporal
Quantities	Selection	Evaluation	Evaluation
Temperature	Module Fig. 3a	$\int$ volume	$\int$ time
Von Mises stress	Bond-wires Fig. 3b	Max(volume)	Max value
Strain energy	Points Fig. 3c	Σ point	Max $\frac{d}{dt}$
Displacement		Max(points)	$\int$ of $\frac{d}{dt}$
Internal energy			Δ value
Stored energy			
Enthalpy			

The different methods of the columns in Table III were combined in all possible ways to yield a large amount of potential loading quantities. The desired format of the final parameter was a scalar describing the relative consumed life time during a single loading cycle. As a result all of the temporal and spacial information contained in the finite element digital twin model must be processed to gain a single scalar.

The first column of Table III lists the different physical quantities evaluated using the FEM software. However, for the software to be able to report this, it is needed to specify 'where' this quantity must be calculated in the model and 'when' to calculate during the simulated cycling period. Column two lists different 'where's to evaluate the physical quantities. Column three list different ways to reduce the field evaluations into a single scalar representing the results of the field. Volume integration is a good example of this, as it reduces the information of the field into a scalar.

Finally column four lists the methods of reducing the time dependant scalars of the previous columns into a scalar expressing the entire duration of the simulated loading cycle.

g) 3. Comparison and Fitting

The final result of this analysis is a large result matrix. Test condition 6 in Table II is omitted from loading factor candidate selection as it will be used as a reference against, which the life prediction of the modelling approach will be tested.

By comparing the R^2 of polynomial fitting of the potential loading factors to the test results the most representative quantity and method was found. In this example it was the Volume Integration over the Bond-wires of the Maximum Rate of Enthalpy. Eq. (1) shows the analytical expression of this quantity.

$$LF = \int_{Bond-wire} max_t\left(\frac{d}{dt}H\right)dV \tag{1}$$

where H is the enthalpy, LF is the loading factor, the integration volume is the bond-wire domain and the $max_t()$ finds the maximum value during the time period.

The On time from Table II and the novel loading factors were fitted to the experimental number of cycles to fail using the "polyfit" function in MATLAB. A second order polynomial was chosen.

h) 4. Prediction using Chosen Loading Quantity

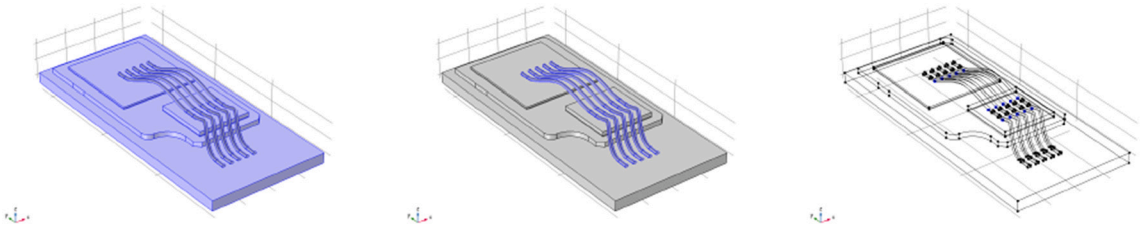
The experimental result of a new loading condition was predicted using these two fitted functions. The results of these predictions, as well as the experimental result of the new loading condition can be seen in Table IV. Here it can be seen that the new loading factor method resulted in a life prediction error with approximately one-third of the error of the loading factor used for life-time model characterization in [11].

5. Discussion

A range of physical quantities were investigated representing both the thermal and mechanical domains in COMSOL Multiphysics, as seen in the first column of Table III. This is not an exhaustive list of possible quantities, but was limited in this way to limit the final matrix of candidates (Table V) from becoming too large. Quantities such as Stress Intensity Factor, different components of the stress tensor or others are all interesting to include in further investigations of this method.

The method has initially been verified with one type of module and one type of accelerated life test. It would be interesting to test the method with different types of module and different accelerated life tests. Additionally this method may be used for other types of electronic components or even other types of test devices.

If a large enough variety of IGBTs and life test strategies were analysed using digital twin models these simulations might also yield



(a) Entire Module (b) Bond-Wires (c) Points in Geometry(In Blue)

Fig. 3. Simulation results for the network.

Table IV
Life-time predictions and their error.

–	Experimental result	Temp swing	Novel method
LF	2.11e5	1.93e5	2.05e5
Error	–	8.78%	2.77%

new insights into which physical quantities are important loading factors for the different loading conditions.

The proposed method is an alternative damage/life modelling approach, existing halfway between empirically fitted equations and time and computationally intensive microstructural damage models.

6. Conclusion

A novel simulation-based loading factor was presented in this paper. The method aims to fill a gap between minimal empirical fitting and costly microstructural analysis. The method relies on a digital twin model of the tested DUT and uses FEM modelling of the experimental accelerated life tests to provide a loading factor representing the loading of the DUT. This factor and the digital twin can then be used for life prediction of new loading conditions.

Appendix A

Table V
Table of R^2 error, lowest value is boldface.

	Temp	Von Mises	Strain energy	Displacement	Internal energy	Stored energy	Enthalpy
PeAiR	1.4763	1.4789	1.4758	1.4788	1.48	1.4758	1.48
PeAisR	1.3718	1.427	1.4608	1.3517	1.3718	1.4608	1.3718
PeAmR	2860.6093	6.8095	0.14882	7.3046	45.4005	0.14882	45.4005
PeAmsR	20.2167	37.646	0.53821	16.9666	20.2167	0.53821	20.2167
PeAmDR	NaN	NaN	NaN	1.4757	6.7687	17.1902	9.5335
PeBiR	1.4763	1.4791	1.4763	1.4788	1.48	1.4763	1.48
PeBisR	1.3716	1.4201	1.4559	1.3429	1.3716	1.4559	1.3716
PeBmR	3074.583	8.1731	0.18978	7.5379	50.7869	0.18978	50.7869
PeBmsR	19.9054	36.3146	0.77961	10.8483	19.9054	0.77961	19.9054
PeBmDR	NaN	NaN	NaN	1.4757	6.7473	13.9357	16.393
ViAiR	1.4759	1.4781	1.4726	1.4773	1.4774	1.4726	1.4774
ViAisR	1.4088	1.3336	1.3973	1.4326	1.4153	1.3973	1.4153
ViAmR	471.7299	1.6234	0.23569	0.51586	0.55335	0.23569	0.55335
ViAmsR	1.0445	18.0819	2.3632	0.41514	0.078414	2.3632	**0.078414**
ViAmDR	NaN	NaN	NaN	1.4757	2.3973	6.1529	46.7661
ViBiR	1.4761	1.478	1.4723	1.4777	1.4791	1.4723	1.4791
ViBisR	1.5075	0.81128	2.5918	1.484	1.5075	2.5918	1.5075
ViBmR	431.3746	1.1003	0.25105	0.53755	1.0264	0.25105	1.0264
ViBmsR	0.4123	1.589	1.1682	0.23408	0.4123	1.1682	0.4123
ViBmDR	NaN	NaN	NaN	1.4757	8.4677	5.0067	4.4579
VmAiR	1.4763	1.4772	1.471	1.4773	1.4745	1.471	1.4745
VmAisR	1.491	1.415	1.3776	1.4229	1.4502	1.3776	1.4502
VmAmR	5282.3561	0.48095	0.43942	0.52342	7.5934	0.43942	7.5934
VmAmsR	14.3501	8.9503	0.17365	0.53242	4.2833	0.17365	4.2833
VmAmDR	NaN	NaN	NaN	1.4757	5.7653	2.3395	0.51654
VmBiR	1.4762	1.4772	1.471	1.4771	1.4797	1.471	1.4797
VmBisR	1.3382	1.415	1.3776	1.4423	1.3382	1.3776	1.3382

(*continued on next page*)

CRediT authorship contribution statement

M.B. Fogsgaard: Conceptualization, Writing - original draft, Investigation, Methodology, Software, Validation, Formal analysis. **F. Iannuzzo:** Supervision, Project administration, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table V (*continued*)

	Temp	Von Mises	Strain energy	Displacement	Internal energy	Stored energy	Enthalpy
VmBmR	5048.9692	0.48095	0.43942	0.41912	98.2408	0.43942	98.2408
VmBmsR	14.6305	8.9503	0.17365	0.75224	14.6305	0.17365	14.6305
VmBmDR	NaN	NaN	NaN	1.4757	5.8212	2.3395	0.51654

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