Review of Burn-In for Production of Reliable Power Electronic Applications

M.sc.ing. Oskars Bormanis
Institute of IEEE
Riga Technical University
Riga, Latvia

Dr.habil.sc.ing. Leonīds Ribickis
Institute of IEEE
Riga Technical University
Riga, Latvia

***Abstract* - Role of burn-in in the life cycle of power electronics assemblies is discussed in this paper. Differences between burn-in and other production screening methods are highlighted. This paper reviews burn-in testing as a part of production reliability improvement program, discussing its benefits and challenges.**

***Keywords* – Reliability engineering, Electronic equipment manufacture, Electronic equipment testing**

I. INTRODUCTION

With increasing both, demand and supply of various consumer electronics products [1], it is easier for new companies to launch products also including power electronics hardware. This is also supported by contract manufacturer market analysis [2] since start-ups tend to outsource their PCB assembly manufacturing services for cost optimization [3], [4]. Accelerated product development and testing can lead to compromised product reliability [5]. Quality of adoption of a new controller or switch technology process is at risk with tight manufacturing and introduction schedule.

The requirement for reliability engineering is not only based on ethical determination to deliver a good quality product. Quality and reliability issues often prove resource-demanding and expensive [6]. Proof of reliability, also as system redundancy is often required by automotive, airplane, military industries. Reliability program can include development stage tests, mass production batch conformance tests [7]. These tests confirm that product is launched with the required reliability level and that product quality is not lost during mass production, demanded by customers which desire to install the hardware in, for example, Tier 4 data centre facilities.

Reliability testing of completed printed circuit board assembly is supported by guidelines published in IPC 9701, evaluating durability of electronics assembly surface mount solder attachments [13], [14], according to which, products are subjected to normal, worst-case, or other realistic operational environments. Burn-in (duration, temperature, sampling) is also discussed in several standards, such as MIL-STD-750 for semiconductor devices, MIL-STD-883 for microcircuits and MIL-PRF-38534 of hybrid microcircuits. While previously mentioned standards describe test conditions of electronics components, they are not easily applicable to burn-in when parts have been soldered on the device under test.

Sourcing of components burned-in at the manufacturer site will reduce infant mortality of power supplies or similar applications. Burn-in is also capable to reveal various assembly defects, process issues and other types of nonconforming products.

II. RELIABILITY TESTS BEFORE BURN-IN

If development stage reliability tests are not performed, results from burn-in become misleading and unstable, due to various product design or material properties. For example, units may overheat due to poor thermal management or malfunction due to cold soldering issues from poor PCB design practice. In order to achieve good quality results from mass production reliability tests and to reduce failure ratio, more attention to detail and time is required to be invested in the development stage tests. There are various reliability and product long-term performance testing methods for development stage [8]. Often time-consuming, requires specialized testing equipment, such as thermal cycling and thermal shock chambers, vibration stands, functional test stands or other automated testing hardware [9], [10], [11]. Development stage can include qualitative tests such as HALT. Team can decide test scale from product reliability requirement, versus testing costs and expected sales.

As mentioned previously, thermal cycling is often used in the reliability testing of lead-free systems. This and other reliability tests provide information about life of the product, according to Arrhenius (1), power-law (2) and Coffin-Manson (3) models for thermomechanical effects [12]. Exponential dependence of time to failure to applied stress according to these models is expressed below:

$$TF = Ae^{-\gamma\xi}e^{-E_a/k_BT} \tag{1}$$

$$TF = B\xi^{-n}e^{-E_a/k_BT} \tag{2}$$

$$Cycles\ to\ failure = (\Delta T)^{-q} \tag{3}$$

where A is a constant related to reaction, TF is time to failure, γ is exponential stress parameter, ξ is generalized stress parameter, T- temperature, k_B – Boltzmann constant, E_a-activation energy, n-power-law exponent, q-material constant, exponent. ΔT could be dormant and active states of the product [46]. These models become helpful to determine burn-in duration for the specific PCBA, to eliminate infant mortality and not over test or under-test the unit.

Performance of major components is often monitored by event detector or data logger, plotting the life span of solder joints using Weibull [9]. Solder joints are a new risk introduced during PCBA assembly. Both, temperature and solder quality are popular reliability risks for power electronics solutions, since thermal and EMI management can involve soldered heatsinks, which have high thermal inertia and difficult solderability.

For power electronics hardware the most common accelerated tests include highly accelerated life test and screening, which combines multiple stresses (temperature stress, humidity, optionally vibration, others) [20] to test new, or currently developed products and their reliability. These tests are often supported by vibration fatigue tests [21], which include sine vibration, random vibration, resonance search, dwell, vibration endurance and others**.** Vibration test failures can include soldering fatigue and break within the mechanical assembly (for example, due to poor heatsink design), as well as short circuits due to opened screws or detached heatsinks. Guidelines for evaluating and extrapolating the results of accelerated reliability tests towards field use environment of electronic assemblies are provided by IPC-SM-785 [15]. Highly accelerated stress screening during mass production (or at the beginning of it) will help to reveal failures which would not be discovered during standard mass production tests [7]. Most of the previously mentioned stress tests for electronic device prototypes usually are designed to be destructive or damaging to the specific unit, since they are intended to find product breaking margin, providing data about performance limits [22]. Destructive tests are not suited for screening of each mass production unit, therefore other testing methods are implemented to assure that product quality is acceptable, performing at the required level during its predicted life.

III. Reliability Tests for Mass Production Units

Post assembly tests for each produced printed circuit board assembly (PCBA) unit such as switch mode power supply can reveal various manufacturing solder or assembly defects, material defects. An additional benefit from PCBA testing is the information about occurring early failure mechanisms [23]. These tests are operating the units and reducing their remaining useful lifetime, which is counter-intuitive. Testing of all production batch units does not improve the reliability of each individual unit, but improves reliability of the batch instead, since poor quality products are stopped at site. This is often accepted to improve overall manufacturing quality. Post assembly reliability tests include basic functionality tests, as well as more advanced tests to eliminate early failing products. Tests include power-up, extended duration function tests, highly accelerated stress screening (HASS), burn-in or run in, environmental stress screening (ESS), and others.

On power-up, test product is powered up in standby mode. Voltage and, optionally, increased ambient temperature is applied [24]. Efficiency is questionable since limited quantity of product nodes are tested. Defects discovered by this test include wrong polarity assembly of electrolytic capacitor (if test time is long enough to trigger capacitor short circuit failure) and other defects in power electronics circuit. It is useful for simple electronic systems such as interface adapters or extension boards with none or few active components.

Depending on product requirements and company policy it may be decided to perform an extended duration function test on several of the production units for extended period of time, revealing component or assembly defects. This could be considered as production batch life test according to parametric binomial approach [25] based on Lipson equality [26], stating that it is possible to extend the test duration, in order to decrease the test sample size [27]. According to these methods it is legitimate to test proportionally small quantity from the manufactured electronics hardware batch for extended time to obtain generalized reliability data of the not tested units as well.

Burn-in is a post-assembly screening process (also run-in [28]), often used to verify that recently assembled electronics hardware products (power supplies, fans, others) can withstand field conditions and will not fail due to manufacturing defects. Setup includes chambers, stands or racks, likely some automated testing equipment as well, to monitor the product performance during the test [29, 30]. Test hardware includes sockets for power and data link between burn-in operator and the tested device. In industry systems of up to 50 unit simultaneously burn-in are common. A balance between test parameters, time and quantity, as well as understanding temperature model throughout the system will help to achieve the best results [29]. Depending on conditions, burn-in can reduce failure period multiple times. Weak population is revealed during the process. If power cycling and increased ambient temperature are applied, inrush current and thermal expansion will further accelerate failure of weak products [30]. Initial charging of capacitors can result in an inrush current which exceeds the rated load current. If circuit is not protected, it can cause voltage in voltage rails to exceed the regulation. It is possible that the current-carrying capability of connectors and PCB traces will be exceeded as well, leading to excess mechanical stress and possible permanent damage [31]. Increased currents of power cycling can make transistors unusable due to small variation in manufacturing since device scaling has exacerbated transistor infant mortality [44]. Multi-layer ceramic capacitors are sensitive to manufacturing process temperatures and mechanical stress as well [45], therefore burn-in currents are capable to reveal the damaged, malfunctioning parts and units. With missing heatsink or thermal grease components will overheat and cause reboot or trigger thermal protection.

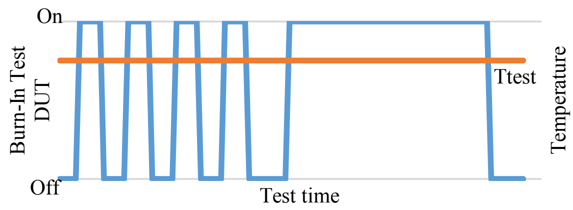

Fig. 1. Burn-in pattern of power cycling and application of constant load, for more advanced stress screening [36]

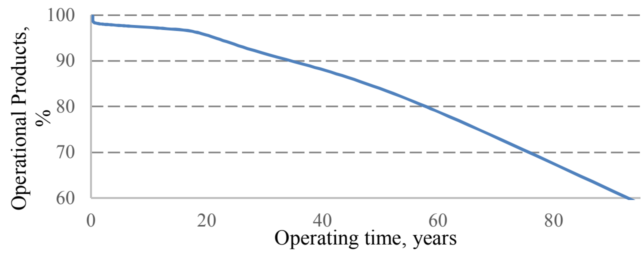

Fig. 2. Sample plot of infant mortality effect on production batch overall reliability in extended operational time

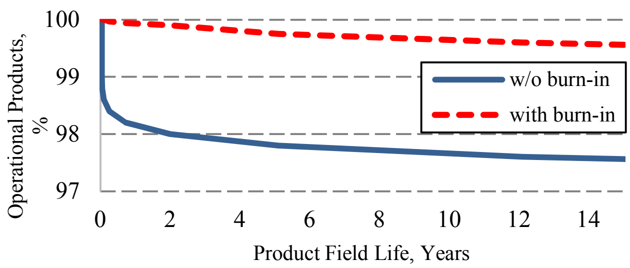

Fig. 3. Illustration of early life failures and wear-out failures during first operational years of a production batch

Fig. 4. Typical burn-in test setup in mass production of consumer-grade power supplies [43]

Sample burn-in pattern is presented in Fig.1, where recently assembled power supply is burned-in at increased ambient temperature and power cycled at the first phase and tested with constant load at the second phase. Such test is effective due to application of power cycling stress, long term operation stress and increased temperatures.

Common causes of failures during the burn-in include fabrication process damage, overheating [32], oxide defects & damage, ionic contamination [33], package defects (cracking), over stress of some application, solder defects (voiding, too less solder), screw/cables not installed properly etc. [31] Human factor can contribute to infant mortality portion of the reliability curve if manufacturing requires high degree of workmanship [7]. It often requires completion of the failure analysis process to evaluate – either the failure of product origins from a manufacturing defect, or it was caused by a wear-out process. Depending on the results of this analysis, a manufacturing defect which causes product failure even after several years still adds to infant mortality. Sample plot of integrated circuit electronics product survival in Fig.2 reveals failure rate decreasing after 3 operational years. During first operational years early failures decrease the overall reliability due to manufacturing defects [33]. The wear-out failure mode is more common later throughout the operational time. If units were stress-tested during manufacturing such that they would leave production as if they had already been operational for 2 years in the field, as shown in Fig.3, then the most of the reliability problems related to early failures would be stopped at the factory, and products in average would survive longer, downside is that all of the parts are shipped with slightly reduced life [33]. Process evaluation criteria include maximum mean residual life, maximum probability of mission success after burn-in [47].

A basic method to accelerate failures of products with quality issues and improve effectiveness (reduce No Fault Found percent) is to increase the temperature in the test chamber. Generalized rule of doubled failure rate by increase of every 10°C in temperature is followed, according to Arrhenius equation. During tests in burn-in chamber at temperature 25°C and 55°C, at higher temperature products should fail about eight times earlier. However, over-use of this rule has been criticized in some literature [34, 35] for being too general and not applicable to all conditions, such as exothermal reactions.

There are several methods to decide if a burn-in is required and how to perform it. When a large PCBA is assembled it has many both, passive and active components. Semiconductor parts are assembled on PCBA and each has their early failure rate. When soldered in one system, individual failure rates are considered for the system as a whole. One approach is to avoid burn-in, by composing system of parts which have been burned-in as single components. If product assembly is introducing new failure modes, burn-in should be performed also for systems assembled with previously burned-in components. Burn-in of the completely assembled system during manufacturing can be skipped if the final system is complex and requires high reliability, but the test conditions are only reasonable to achieve at the actual operating site [32]. Depending on the procedure, products which fail in burn-in are returned for analysis, reworked or scrapped.

In reliability engineering, the exponential distribution is very common. MIL-HDBK-217 handbook assumes that most electronics can be modelled by exponential distribution with constant failure rate [36]. Handbook contains data for passive and active elements: resistors, transformers, transistors, FETs, and others [37], leading to conclusion that burn-in of these components to eliminate failures is not practical. If products with increasing failure rate, β>1, or ones with exponential failure distribution and constant failure rate (β=1) are being tested, reliability will be decreased after the test, compared to products which were not tested. Assembly will wear-out during the burn-in, decreasing time to actual field failure, without eliminating infant mortality defects which are not common for parts with β ≥1 [33]. For efficient burn-in application, tested product should have a failure rate which decreases over time, β<1 in Weibull distribution [36]. Parts with decreasing failure rate β<1 of Weibull distribution are presented in Fig.3. Such manufacturing defects can take up to 10 years to reveal, for example, integrated circuits (IC) industry has observed failures driven by manufacturing caused defects even after ten years of operation [33]. Fig.3 shows typical distribution of complex electronic products, such as CPU or GPU.

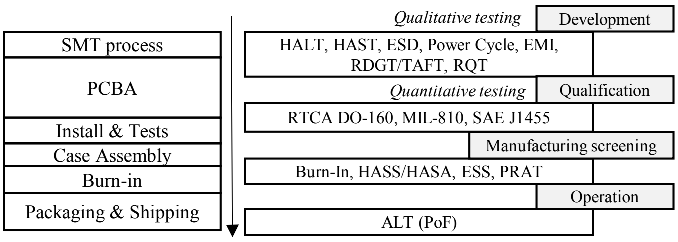

Fig. 5. Place of burn-in in product development flow and typical mass production of electronic devices

IV. BURN-IN FOR PCBA OF POWER ELECTRONICS

One of the burn-in system types is static burn-in. The device under test is placed in burn-in chamber, where elevated temperatures optionally are applied over the test duration. In static burn-in lack of external biases make the burn-in stress less effective for complex systems [29]. In a dynamic burn-in system device under test is tested at maximum rate limited by burn-in chambers, which apply power stimulation and stress to internal nodes of the device. Like static test, for various reasons dynamic systems do not track device response during the test itself, meaning that failure can only be identified during follow-up functionality tests and is a limitation [29].

For high-reliability products of automotive industry burn-in in temperature cycling chambers is often a requirement [38] to verify product durability margin. This burn-in test can last several days, during which modules are supplied with voltage, and functional tests at changing temperatures are performed.

It is possible to combine functional test with burn-in, then product performance is monitored, such as fans, CPU, RAM, GPU, e.g. If installation or some functional test is required besides burn-in, the product must be powered up in order to install it. This short power-on is not a burn-in. Although function tests will reveal manufacturing defects, these defects usually are not the infant mortality of the bathtub curve.

In product development flow burn-in is one of manufacturing screening methods, scheduled between functional tests and packing, or even as a part of the installation and functional test (see Fig.5). Depending on requirement and available infrastructure, it is decided if burn-in will take place in chambers or other types of stands as shown Fig.4. After successful burn-in, products are moved to packaging.

Consumption of electrical energy during burn-in is a small concern in manufacturing of low power devices, while burn-in of 500W and power supplies with higher output power, lead to high total energy consumption during burn-in, as a lot of units are operating at rated power simultaneously for an extended period of time. Energy recycling methods have been discussed earlier and approved and implemented by industry. They typically include AC/DC rectifier and DC/AC inverter connected with the device under test, and topologies such as capacitive idling converter (see Fig.6) have been presented earlier [48].

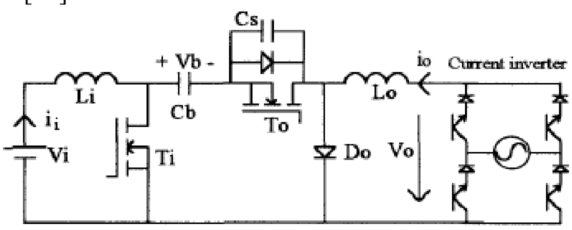

Fig. 6. Sample of capacitive idling Cuk converter for burn-in energy recycling (return to the grid) applications [48]

Quantity of products in burn-in batch depends on the method, test duration and expected output. Either all production units will be tested, or the first from each batch first batch, or random units from current mass production as a burn-in audit. Acceptance sampling can be used for quantification of burn-in samples as well. Both – test method and product quantity will have an impact on burn-in results.

The third of the major parameters for the burn-in test, besides test method and test quantity, is time. It is highly product-specific, therefore varies for each setup and product. Semiconductor burn-in time is junction temperature-dependent and due to significant power variations in processing, some devices will become hotter and reach potential thermal runaway. In some power electronics solutions condition monitoring is a cost-effective alternative to burn-in, and currently a hot topic in the power electronics, as well as ESS, HASS or HASA are often discussed as an alternative.

V. OPTIMUM BURN-IN TIME

Several factors from the assembly process can contribute to product failure during burn-in. It is reasonable to burn-in the recently assembled system to sort them out. Benefits such as improved production batch overall reliability and decrease of early failures are discussed previously. However, duration of burn-in is often a compromise between production cost and reliability goal for the product and determination of optimum time for burn-in is required. Some of the costs related to burn-in include cost of burn-in, cost of unit warranty returns, cost of lost items and cost of failure. Optimum burn-in time can be determined corresponding to zero slope of the failure rate curve, corresponding to a specified failure rate goal, or corresponding to a specified reliability goal [39]. Most products are designed with cost-reduction requirements throughout all development phases. Product manufacturing testing managers must decide which (if any) tests are required for current product production flow and which are optional, or too expensive for product target price.

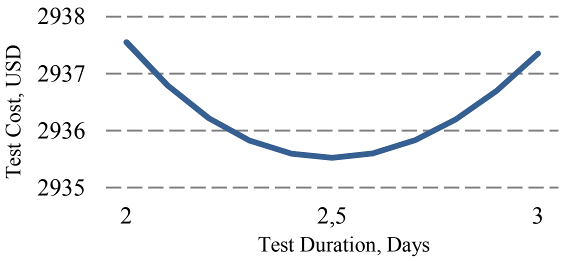

Fig. 7. Sample plot of optimum power electronics burn-in cost and time relationship considering the cost of product and warranty returns

If a PCBA project is a part of a larger system and would run through burn-in after assembly as well, it is sometimes decided to skip the first burn-in. To test both PCBA separated development and maintenance of two testing systems is required. Combined test reduces required equipment quantity and therefore test equipment cost. However, one should consider expenses for disassembly and handling of failed units. If assembly is complicated, it can prove more effective to test all of the PCBA before assembly.

Cost of the process has a high priority to determine duration of the burn-in. Since this cost is directly related to manufacturing duration, total burn-in cost consideration includes time required for testing and rework. It also includes scrap cost of failed products, cost of warranty failures (incl. replacements, shipping, etc.), and other related costs. During the design of product testing phase, burn-in setup, time and quantity are considered. Burn-in scrap or rework costs are approximated, as well as warranty replacement or repair costs. With all these costs and estimated number of failures in burn-in test and estimated quantity of field failures during warranty period, it is possible to calculate optimum burn-in time. For example, if power electronics hardware replacement during warranty costs 4000 USD, one burn-in day per unit costs 70 USD, failures during burn-in cost 500 USD, then cost-optimum burn-in period is 2.3 days, with expected total cost of 2935,52 USD [40] (see Fig. 7). These are not direct costs of testing and repairs, but is a value used for balancing of burn-in time, quantity of product replacement during warranty and number of failures during burn-in. For better understanding of this cost value, if burn-in period is approaching 0, the total costs would approach 4000 USD, because unit would be likely to fail during warranty. For burn-in to become financially reasonable, cost per field failure should exceed the cost per burn-in failure, or product testing cost exceed the product replacement cost. Engineer should take account of not only directly measurable effects, but not directly measurable parameters as well, such as lost market gap and decreased customer satisfaction due to early field failures.

Similar to deploying a reliability test does not end the product reliability program, analysis of the burn-in results is a crucial step after the test is completed. It is possible to compare the results to expected reliability goals, evaluate the observed failure mechanisms and reevaluate the design [16]. For example, reliability team analyzes the results of burn-in to create instructions for further actions and scenarios, such as if some predefined failure rate is exceeded and batch products fail more than expected. If not all of production units are burn-in, mathematical statistics (acceptance quality level) will support the decision how to continue if several of the tested units fail at burn-in, what actions are required regarding the rest of the production batch.

Development and post-assembly reliability test results can be analyzed following Failure Modes Effects and Criticality Analysis (FMECA) [41]. Each of the tests (development or production) can expose different failures due to various failure mechanisms and various stresses applied during the test. FMECA results should be implemented in production and development to improve performance of further production batches. The responsible team should consider information from these failures and evaluate possible quality improvements [42]. The results of this analysis lead to reduction of burn-in test batch, reduced testing time or setup changes.

VI. Conclusions

Accelerated product development for the specific launch window is a risk for the reliability of electronics assembly. Tests of the development stage are destructive and useful for product performance margin determination, therefore other methods are required for mass production. Although post assembly screening reduces each individual product remaining useful lifetime, overall quality of the remaining production units is improved. Burn-in is a post-assembly process, in which products can be tested in ambient or increased temperature, by power cycling or by application of constant load. If applied, considering cost, target price and target reliability, burn-in is used to accelerate early failure mechanisms and to sort early failing products. Most likely burn-in is located in mass production site and is a part of standard manufacturing process. The role of optimum burn-in time calculation is to support final decision of the test duration and optimize the production and warranty return costs. Major challenges of deploying a burn-in in production are capital costs of the setup, reduction of pass yield during production tests and increased overall production costs, whereas benefits include customer satisfaction and decreased risk of an expensive early failure.

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Oskars Bormanis received B.Sc.eng and M.Sc. of Riga Technical University, Latvia at 2014, 2015, at the field of Electrical Power engineering. He is a PhD student at Riga Technical University, Institute of Industrial Electronics and Electrical engineering, and is employed by networking hardware manufacturer as electronics quality engineer. His research focuses on reliability within intelligent industrial DC power distribution systems, including reliability improvement practice for electronics development and manufacturing

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