TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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Development and Evaluation of Accelerated Environmental Test Methods for Products with High Reliability Requirements

Julkaisu 1242 • Publication 1242

Tampere 2014

Tampereen teknillinen yliopisto. Julkaisu 1242
Tampere University of Technology. Publication 1242

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Development and Evaluation of Accelerated Environmental Test Methods for Products with High Reliability Requirements

Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Tietotalo Building, Auditorium TB109, at Tampere University of Technology, on the 3rd of October 2014, at 12 noon.

Tampereen teknillinen yliopisto - Tampere University of Technology
Tampere 2014

ISBN 978-952-15-3359-4 (printed)
ISBN 978-952-15-3381-5 (PDF)
ISSN 1459-2045

ABSTRACT

Reliability testing of electronics is performed to ensure that products function as planned in specific conditions for a specified amount of time. This is usually both time-consuming and expensive and therefore test time acceleration is often required. The acceleration may be realized by using more severe stress levels or higher use cycle frequencies, but at the same time the risk increases of inducing failure mechanisms not relevant to the use conditions. As a consequence, the accelerated reliability testing of products with markedly long lifetimes and high reliability is frequently challenging.

In this thesis different methods for test time acceleration for products with high reliability requirements and long service lives were studied. Both standard tests and modifications of these were used. The effect of the accelerated tests used on the failure modes and mechanisms observed was examined and the limitations of the test methods discussed. The research in this work was conducted at both interconnection level and at device level. The interconnection level testing focused on anisotropically conductive adhesive (ACA) flex-on-board (FOB) attachments. In addition to the effect of the curing process on the mechanical strength of ACA FOB attachments, their applicability and long-term performance in industrial applications was studied. According to the real-time resistance measurement the assembly tested was observed to be extremely resilient in thermal cycling and hygrothermal aging. However, a significant decrease in the mechanical strength of the FOB attachment was also seen. Hydrolysis and embrittlement of the flex material was also observed to limit the applicability of harsher hygrothermal aging conditions. Clear ACA joint failures were only observed with moisture condensation testing, but this may not be a suitable test method for applications that are not susceptible to such a stressor.

The device level testing comprised reliability analysis of two frequency converter models. The older generation device and its field failure data were used as the starting point in the development of a test method that could be used to minimize testing time and to induce comparable failure modes to those occurring in the use conditions of the devices. The tests showed that only with the simultaneous use of stresses could a significant reduction in the testing time be achieved. However, the application of the same test method to the newer generation device proved challenging because of differences in materials, components and layouts. Although similar failure modes were observed in both devices, the combined effect of the stresses used on the failure mechanisms requires further study. In addition, knowledge of the service conditions, the environmental stresses and their severity is critical. The main disadvantage of simultaneous stress testing was observed to be the interpretation of the test results, especially due to the complexity of the devices tested. Moreover, the results obtained may be highly application specific. However, regardless of the difficulties in the lifetime estimation, the use of combined stresses was observed to be a practical method to study the weaknesses in a product.

ACKNOWLEDGEMENTS

This work was carried out at the Department of Electronics and the Department of Electrical Engineering of the Faculty of Computing and Electrical Engineering at Tampere University of Technology (TUT) during the period 2005-2014.

This work was supported financially by the Ulla Tuominen Foundation and the EIS Foundation, whose support is here gratefully acknowledged.

First and foremost I wish to thank my supervisor Adjunct Professor Laura Frisk for her encouragement and support. Her guidance regarding my research and her contribution as the main co-author were essential for the completion of this thesis. I also want to thank my former supervisor, Pekka Heino, D.Sc., for his help at the beginning of my studies. In addition, I wish to express my gratitude to Sampsa Kuusiluoma, M.Sc., for introducing me to this interesting research topic and for his help and guidance during my first years as a researcher. I also wish to thank my other co-author Maija Hoikkanen, D.Sc., for her help. Furthermore, I wish to express my gratitude to the pre-examiners Adjunct Professor Olli Salmela and Professor Ephraim Suhir for their valuable comments and suggestions.

I am very grateful to have had the opportunity to work in the Packaging and Reliability Group and I wish to express my sincere thanks to my past and present colleagues for all their help during the years. Especially, I owe my gratitude to Kati Kokko, D.Sc., Kirsi Saarinen, D.Sc., Sanna Lahokallio, M.Sc., Juha Pippola, M.Sc., Tuomas Marttila, M.Sc., and Milad Mostofizadeh, M.Sc., for their encouragement and fruitful discussions on more or less scientific topics.

Finally, and most of all, I want to thank my girlfriend Kati, my parents Toini and Kari, my sister Sanna as well as Jukka and Jan for believing in me and for the indispensable support you have given me over all these years.

Tampere, August 2014

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LIST OF PUBLICATIONS

This thesis consists of an extended summary and the following publications:

I. Kiilunen, J., Frisk, L. and Hoikkanen, M. “The Effect of Bonding Temperature and Curing Time on Peel Strength of Anisotropically Conductive Film Flex-On-Board Samples”, IEEE Transactions on Device and Materials Reliability, Vol. 12, No. 2, 2012, pp. 455-461.

II. Kiilunen, J. and Frisk, L. “Reliability Analysis of an ACA Attached Flex-On-Board Assembly for Industrial Application”, Soldering and Surface Mount Technology, Vol. 26, No. 2, 2014, pp. 62-70.

III. Kiilunen, J. and Frisk, L. “Hygrothermal Aging of an ACA Attached PET Flex-on-Board Assembly”, IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 4, No. 2, 2014, pp. 181-189.

IV. Kiilunen, J. and Frisk, L. “System-Level Reliability Testing a Frequency Converter with Simultaneous Stresses”, IET Power Electronics, Vol. 4, No. 8, 2011, pp. 884-890.

V. Kiilunen, J. and Frisk, L. “Reliability Analysis of Two Frequency Converter Generations Using System-Level Stress Testing”, IET Power Electronics, Vol. 5, No. 7, 2012, pp. 1042-1048.

AUTHOR’S CONTRIBUTION

Publication I, “The Effect of Bonding Temperature and Curing Time on Peel Strength of Anisotropically Conductive Film Flex-On-Board Samples”, was accomplished by the present author together with the co-authors as follows: the tests were planned with the help of L. Frisk, the test samples assembled, the testing carried out, and the results analysed by the present author. The DSC analysis was conducted at the Department of Materials Science at Tampere University of Technology by M. Hoikkanen. The SEM analysis was conducted at the Department of Materials Science at Tampere University of Technology under the supervision of the present author. The present author wrote the manuscript with the help of the co-authors.

Publication II, “Reliability Analysis of an ACA Attached Flex-On-Board Assembly for Industrial Application”, was accomplished by the present author together with the co-authors as follows: the tests were planned with the help of L. Frisk, the test samples prepared, the testing carried out, and the results analysed by the present author. The SEM analysis was conducted at the Department of Materials Science at Tampere University of Technology under the supervision of the present author. The present author wrote the manuscript with the help of the co-author.

Publication III, “Hygrothermal Aging of an ACA Attached PET Flex-on-Board Assembly”, was accomplished by the present author together with the co-authors as follows: the tests were planned with the help of L. Frisk, the test samples assembled, the testing carried out, and the results analysed by the present author. The SEM analysis was conducted at the Department of Materials Science at Tampere University of Technology under the supervision of the present author. The present author wrote the manuscript with the help of the co-author.

Publication IV, “System-Level Reliability Testing a Frequency Converter with Simultaneous Stresses”, was accomplished by the present author together with the co-authors as follows: the tests were planned, the test equipment realized, and the tests carried out with the help of S. Kuusiluoma, the results were analysed by the present author. The present author wrote the manuscript with the help of the co-author.

Publication V, “Reliability Analysis of Two Frequency Converter Generations Using System-Level Stress Testing”, was accomplished by the present author together with the co-authors as follows: the tests were planned and the test equipment realized with the help of S. Kuusiluoma, the tests carried out, and the results analysed by the present author. The DSC analysis was conducted at the Department of Materials Science at Tampere University of Technology. The present author wrote the manuscript with the help of the co-author.

LIST OF ABBREVIATIONS AND SYMBOLS

ABS/PC	Acrylonitrile-Butadiene-Styrene / Polycarbonate
AC	Alternating Current
ACA	Anisotropically Conductive Adhesive
ACF	Anisotropically Conductive Film
AF	Acceleration Factor
CDF	Cumulative Distribution Function
CTE	Coefficient of Thermal Expansion
DC	Direct Current
DSC	Differential Scanning Calorimetry
FC	Frequency Converter
FET	Field-Effect Transistor
FIT	Failures in Time
FOB	Flex-on-Board
HALT	Highly Accelerated Life Testing
ICA	Isotropically Conductive Adhesive
IGBT	Insulated Gate Bipolar Transistor
I/O	Input/Output
LCD	Liquid Crystal Display
LCP	Liquid Crystal Polymer
PCB	Printed Circuit Board
PC/GF	Polycarbonate with Glass Fibre Reinforcement
PDF	Probability Density Function
PEN	Polyethylene Naphthalate
PET	Polyethylene Terephthalate
PI	Polyimide
PWM	Pulse Width Modulation
SMT	Surface Mount Technology
β	Weibull Distribution Shape Parameter
η	Weibull Distribution Characteristic Lifetime
γ	Weibull Distribution Location Parameter

ΔT_{test}	Temperature Cycling Range in Test Conditions
ΔT_{use}	Temperature Cycling Range in Use Conditions
E_{a}	Activation Energy
$f(t)$	Probability Density Function
$F(t)$	Cumulative Distribution Function
$h(t)$	Hazard Rate
k	Boltzmann's Constant
m	Empirically Determined Constant
M_{test}	Relative Humidity Percentage in Test Conditions
M_{use}	Relative Humidity Percentage in Use Conditions
n	Material Constant
n_i	Number of Applied Cycles at Stress Level i
N_i	Cycles to Failure at Stress Level i
N_{test}	Cycles to Failure in Test Conditions
N_{use}	Cycles to Failure in Use Conditions
$R(t)$	Reliability Function
R_{Sample}	Resistance of a Test Sample
R_{Ref}	Resistance of the Reference Resistor in the Real-time Measurement System
t	Time
T_{g}	Glass Transition Temperature in Degrees Kelvin
T_{test}	Temperature in Test Conditions in Degrees Kelvin
T_{use}	Temperature in Use Conditions in Degrees Kelvin
V_{S}	Power Supply Voltage in the Real-time Measurement System
V_{Sample}	Voltage of a Test Sample in the Real-time Measurement System

1 INTRODUCTION

Advances in semiconductor technology, miniaturization and system integration have enabled electronic devices in various forms and applications to become an essential and sometimes even inseparable part of our everyday lives [Har97][Har02][Tumm97a]. This dependency on electronics will most likely continue to increase in the future due to the electronics industry's continuous effort to provide products offering higher quality, higher performance and lower cost. In consequence, the requirements on the reliability of these devices will likewise increase, thereby creating additional challenges for electronics manufacturers.

Electronic products may be subjected to a wide variety of stresses during their lifespan depending on the application and service environment [Jen95][Kly06][Ohr98]. If the effects of these stresses are not sufficiently taken into account during the development phase of a product, reliability concerns may arise during its lifetime [Bho04][Oco05]. This in turn may cause high warranty costs for the manufacturer and loss of customers. In the worst case, the lack of reliability may result in personal injuries or environmental disasters. To avoid this, manufacturers commonly conduct environmental tests that aim to study, improve, and verify the reliability of products [Jen95][Oco05]. The downside is that reliability testing requires planning, test capacity and personnel to conduct the testing and analyse the results, thus likely making it very time consuming and expensive. This, on the other hand, contradicts with manufacturers' aim to minimize the time-to-market, i.e. the time required to develop and launch a new product in order to beat the competition. Another important factor for manufacturers is production cost. In other words, in order to keep expenses down the robustness of a product needs to be optimized according to its use environment, reliability requirements and planned service life [Oco05]. Therefore test methods are needed that can be most efficiently used to study not only when, but also how and why products fail in the field.

Because the lifetimes of electronic products in some applications may be very long, it is not practical to study their reliability in normal use conditions for extended periods of time. Therefore testing time is often reduced by using accelerated test methods where a product is subjected to more severe stresses or to a higher usage rate that it would normally experience during use [Kly06][Nel04][Por04][Suh02]. However, this also serves to increase the risk of causing the product to fail in an unrealistic manner [Meeker98]. In other words, if failures not relevant to the actual use conditions occur, no usable information is obtained from the test. In the worst case, incorrect conclusions are made on the basis of inaccurate test results and unnecessary changes may be implemented in the product. This is challenging for the planning of accelerated tests and for the interpretation of test results, especially in products that are designed to be extremely reliable and with long lifetimes.

1.1 OBJECTIVES AND SCOPE OF THE THESIS

The object of this study was to examine the effect of parameters of different reliability testing methods on the overall test times as well as on the failure modes and mechanisms of tested samples. The test methods studied included commonly used test standards and modifications thereof. In addition, the aim was to study how testing time could be reduced in the case of products with long service life and high reliability requirements. The research conducted in this work is divided into two parts: reliability testing at interconnection level and at system level. The first part, interconnection level testing, addresses the usage of flexible circuits in a display device application used with frequency converters as well as the properties and process parameters of anisotropically conductive adhesives. In addition, the applicability of using inexpensive flex connector material with adhesive attachment techniques in harsh industrial environments was examined. In the second part of this thesis the system level reliability of a frequency converter was examined by using various stresses separately and concurrently. The aim was to study the effects of simultaneous stress testing on test time and on the failure modes and mechanisms observed. In addition, the object was to examine if a test method could be developed for an old generation device based on its failure data from service conditions that could then be used to study the reliability of a new product design.

1.2 STRUCTURE OF THE THESIS

This thesis consists of an extended summary followed by five publications. The extended summary is divided into five chapters, which provide relevant background information on the topic and present the main results. Chapter 1 gives a general introduction to the topic. Chapter 2 introduces basic reliability concepts and the theory behind reliability testing. Chapter 3 discusses reliability testing at interconnect level and the use of anisotropically conductive adhesives. In this chapter the test samples, test setups, and the test methods used in this study are described. In addition, the reliability test results are discussed. Chapter 4 discusses reliability testing at system level in the case of a frequency converter. The test samples and the test methods used in this study are described and the reliability test results are presented. The final conclusions and a summary of publications are presented in Chapter 5.

2 ELECTRONICS RELIABILITY

Customers today require electronics products of high quality, high performance, high functionality and low cost. In addition, the certainty that a product will function as planned throughout its service life is of great importance to manufacturers. This is especially true in situations where shortcomings in product reliability may cause not only customer annoyance but also high repair costs, expensive process downtime, or even personal injuries. On the other hand, designing a product that is too robust for a particular application may take too long and not be cost-effective. Therefore, compromises have to be made between the needs for product reliability, cost effectiveness, and time-to-market [Suh13].

2.1 RELIABILITY CONCEPTS

In engineering the term reliability is defined as the probability that a product will perform its intended function under stated operating conditions for a specified amount of time [Rel57][Jen95][Ohr98]. In this definition the product may mean a single component or a larger system and the operating conditions comprise all the environmental stresses and occurrences that the product will face during normal use. However, instead of studying how well products survive, reliability engineering is usually more concerned with how many are expected to fail in a specific period of time [Jen95]. The aim of this practice is to use statistical methods to obtain lifetime information on products in specific conditions, which can then be used to make probability estimations. This method is also known as quantitative testing [Esc06]. In addition to reliability statistics, another important concern is to understand how and why the products fail. This research concentrates on examining the different ways a product may fail in use and on the mechanisms causing these failures. This study of failure physics is also known as qualitative testing and is the main focus of this study [Esc06][Ohr98].

2.1.1 Reliability parameters

The aforementioned definition for reliability is also known as the reliability function, $R(t)$. It can be used to calculate the probability that a product will remain operational after a certain period of time of use, i.e. the probability of survival. The complement of the reliability function is the cumulative distribution function (CDF), $F(t)$. It is used to describe how failures accumulate as a function of time or, in other words, the probability of failure. Another commonly used reliability metric is the probability density function (PDF), $f(t)$ [Jen95][Nel04]. This function gives the probability that a product will fail within a specific time interval, or in other words, it describes how the failures are distributed over time. The PDF is obtained by taking the first time derivative of the CDF:

$$f(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}t} \tag{1}$$

The function describing the number of products failing at a given instant is called the failure rate or hazard rate, $h(t)$. The commonly used unit for the hazard rate is the failures in time (FIT). It is often given in the form of failures per 10^9 hours. The failure rate function is obtained by:

$$h(t) = \frac{f(t)}{R(t)} \tag{2}$$

The failure rate of an actual product can be observed to change during its life cycle. This change is commonly represented with a so-called bathtub curve (Figure 1.). During early life the hazard rate is commonly very high, which may be caused by intrinsic failures in components and materials due e.g. to manufacturing problems, process variability, and inappropriate handling or assembly procedures. Because of this, a population of products may suffer from a high infant mortality rate as weak specimens fail early on. In order to avoid high warranty costs attempts are normally made to screen out the items susceptible to infant failures before the products are sent to customers. After the weak items have been removed the failure rate becomes fairly constant. This is the useful life period when only a few random failures are usually observed. In the last part of a product's life cycle the failure rate again increases as differing wear-out mechanisms have taken effect and caused deterioration in the product's strength. It is important for manufacturers to be able to determine and minimize the failure rate during the early and useful life of a product. In addition, in order to ensure that the wear-out period exceeds the desired operational lifetime of a product, long-term testing may be required. However, it should be observed that the bathtub curve described here is a generalization and it may not always be an accurate representation of real life situations. In other words, the failure rate curve may fluctuate markedly during the lifetime of a product and the differentiation of the aforementioned lifetime periods may be difficult [Jen95].

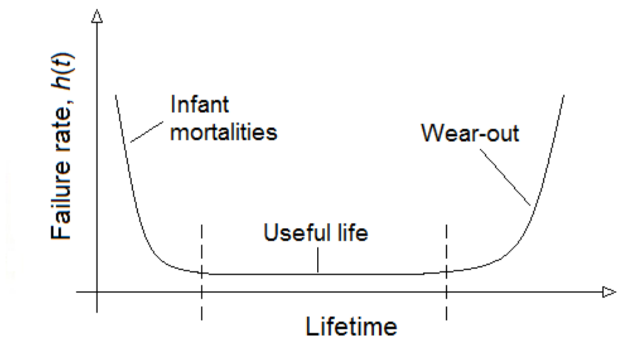

Figure 1: Failure rate bathtub curve.

2.1.2 Statistical analysis and life distribution models

The aim of quantitative testing is to demonstrate the reliability or to predict the performance of a product population based on time-to-failure data [Mee95]. Because this is normally accomplished by testing a limited number of sample products, these items therefore need to be representative of the whole population. Furthermore, the number of tested samples needs to be high enough in order for the results to be statistically significant. The determination of sample size depends on e.g. what reliability metrics need to be quantified, what the required confidence interval and confidence level are, how long the samples can be tested, and if prior statistical knowledge can be utilized [Nel04][Mee95][Guo13]. Therefore the exact number of samples required varies case-by-case and may range from several dozens to several hundreds. For example, in the particular case of surface mount solder joints IPC-SM-785 standard recommends a minimum sample size of 32 if the test is continued until at least half of the samples have failed [IPC92]. In practice, these requirements may be difficult to meet because of high costs or limited availability of samples [Ma10]. Consequently, compromises between sample sizes and statistical confidence are often necessary.

In order to analyse the failure data and to obtain the required statistical information and reliability parameters, different mathematical methods can be utilized. This is done by finding the distribution function that best fits the failure data. Distribution functions are theoretical population models that can be used to describe the lifetimes of a sample population. In the case of electronics reliability the most commonly used distribution models are the normal, the log-normal, the exponential and the Weibull. From these only the Weibull distribution is discussed in this work. It is a versatile and widely used model. [Jen95][Ohr98]

The Weibull distribution, named after a Swedish scientist Waloddi Weibull, was originally used to describe the life properties of ball-bearings, but it has since been observed to apply in cases where the weakest link amongst many flaws propagates to failure [Ohr98][Jen95]. The two main parameters characterizing the Weibull distribution are the characteristic lifetime (η) and the shape parameter (β). The characteristic lifetime gives the time when 63.2 % of the samples in a population have failed. The shape parameter instead describes the shape of the distribution and by varying its value the Weibull distribution can be changed to model the differing failure rates illustrated in Figure 1. With $\beta < 1$ the distribution depicts a decreasing failure rate, whereas with $\beta > 1$ the distribution models a population with an increasing failure rate. With $\beta = 1$ the distribution corresponds to a constant failure rate. In this particular case the Weibull distribution resembles the exponential distribution. The third parameter of the Weibull distribution is the location parameter (γ). This parameter moves the PDF along the time-axis and can be used to model failure-free time. However, in most practical cases γ is assumed to be zero [Jen95].The CDF for the three-parameter Weibull distribution is:

$$F(t) = 1 - e^{\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right]} \quad (3)$$

2.2 FAILURE PHYSICS

Although quantitative testing and statistical analysis are an important part of reliability engineering, information is also needed on the failures themselves. The only way to efficiently minimize the number of failures or to prevent them altogether is to understand what factors affect the performance degradation of a product in use conditions and how they eventually cause it to fail. These questions can only be answered by performing a root cause analysis on failed products in order to identify the weakest links reliability-wise and their reasons to this. [Ohr98][Mar99]

2.2.1 Failure modes and mechanisms

The main objective of failure analysis is to determine the root cause due to which a product has ceased to operate and to obtain information on how this could be prevented [Mar99]. In this research the terms failure mode and failure mechanism are generally distinguished from each other. The term failure mode is used to describe the indications through which a failure is observed [Ohr98]. In the case of electronic components the failure modes may be classified, for example, as short circuits, open circuits, degraded performance, or functional failures [Jen95].

On the other hand, the failure mechanisms describe the differing processes that have led to the observed failure mode. Different failure mechanisms may also cause the same failure modes. Failure mechanisms may be classified into mechanical, thermal, chemical, electrical and radiation failure types according to the stresses and loads that inflict them [Tum97b]. Examples of such failure mechanisms are shown in Table 1. With electronic components the dominant failure mechanisms include corrosion, creep, fatigue, and wear [Mar99][Oco05].

Table 1: Failure mechanism examples classified based on differing stresses [Tum97b][Mar99][May07].

Mechanical:	Thermal:	Chemical:	Electrical:	Radiation:
Creep	Thermal expansion mismatches	Corrosion	Dielectric breakdown	Gate oxide breakdown
Fatigue	Dimensional changes	Oxidation	Electromigration	Latchup
Interfacial delamination	Changes in physical properties	Ionic dendritic growth	Electrolytic corrosion	Burnout
Brittle fracture		Diffusion	Power dissipation heating	Encapsulant depolymerization
Ductile fracture		Intermetallic formation		

2.2.2 Environmental stresses and stress levels

Various kinds of environmental stresses affect products during their manufacture, shipping, storage and operation. These include, for example, high and low temperatures, temperature fluctuations, vibration, mechanical shocks, high humidity, voltage fluctuations, electrostatic discharges, corrosive atmosphere and dust. What kind of stresses a product faces and how severe they are depends greatly on the application itself and on the use environment. Therefore, in order to design a reliable product, information about the service conditions is required. Furthermore, knowledge about the factors affecting reliability may make it possible to reduce the risk of over-engineering a product, and also the production costs. [Mar99][Oco05]

The stress levels of each environmental stress a product is subjected to can be classified in different ways. Design stress or specification limits may be used to describe the stress levels that are either based on manufacturer's specifications, customer requirements, or maximum stress levels in the actual use conditions. If a stress level is increased, products will finally reach their destruct limits, i.e. the stress values from which a product does not recover even if the stress is lowered. For example, in the case of thermal stress the destruct limit for a solder attachment could the melting temperature of the solder. The stress levels that cause transient and reversible failures may instead be defined as operational stresses. [Bho04][Oco05]

2.2.3 Stress-Strength

In practice, the stresses or loads to which products are subjected in use conditions usually consist of a range of values rather than one specific value. In the same way the strength of a population of products can be assumed to be statistically distributed. In this context the product strength is defined as the stress level that causes an instantaneous failure. If the minimum strength value of a product exceeds the maximum stress value, the probability of failure is zero and the product will not fail. This situation is illustrated in Figure 2. However, due to wear-out or degradation mechanisms the product strength may start to decrease over time, which in turn causes the margin between the stress and strength distributions to decrease. When the two distributions overlap each other wear-out failures will start to occur (Figure 2). If the strength and stress distributions already overlap at the beginning of a product's lifetime, it is likely that infant mortalities will occur at use conditions. [Ohr98][Jen95][Oco05][Vis98]

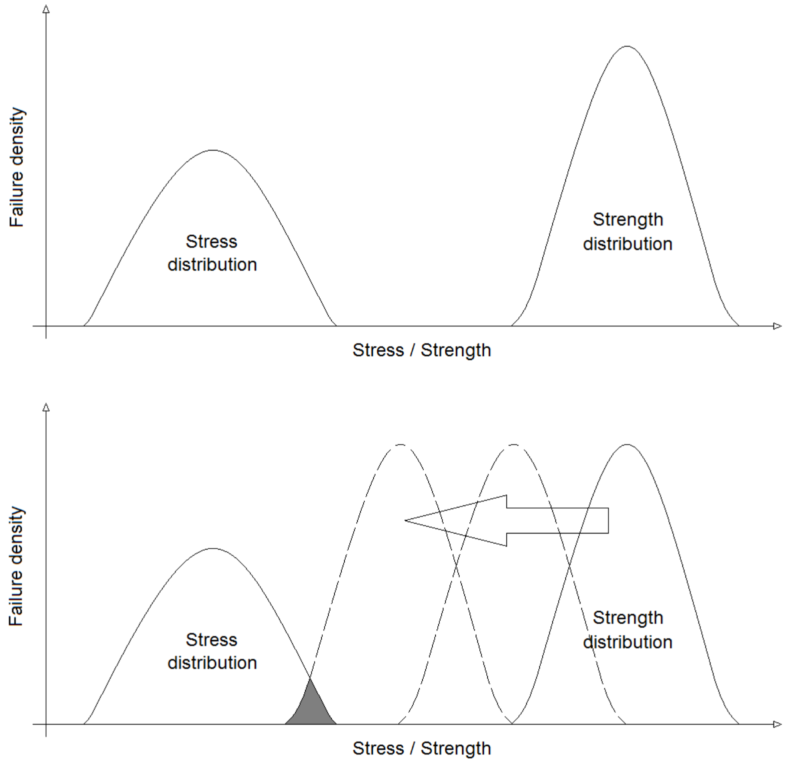

Figure 2: The effect of wear-out or degradation mechanisms on the strength distribution of a product.

2.3 ACCELERATED RELIABILITY TESTING

The fact that the lifetimes of products may be substantially longer than the product development cycles poses a challenge to reliability testing. Not only is reliability testing time consuming and costly, but product manufacturers also often aim to minimize the "time to market" in order to stay ahead of the competition. Therefore test time is often shortened by using accelerated reliability testing. The acceleration is normally performed by using higher stress levels and higher usage rates than those to which a product would normally be subjected during operation. [Suh02][Nel04][Oco05]

Reliability testing is usually based on specific standards either selected by manufacturers or demanded by customers or legislation. The advantage of standardized tests is that they can provide guidelines for performing the tests and they serve as benchmarks for the reliability results. In other words, they can be used to demonstrate compliance as well as enable reproducibility and comparability of test results. However, there are many standards to choose from and not all are applicable in every situation. Therefore the selection of the test standard and the stress level used should be made carefully on the basis of knowledge about the product to be tested and its whole life cycle. Otherwise the results from a standard test may not be applicable in real life. Test methods can also be tailored and modified in order to better adapt them to the actual service life of a product. For example, MIL-STD-810G emphasizes the tailoring of environmental design and test limits to the service life conditions of a specific product [Dep08]. The objective is not to reproduce the use environment in laboratory conditions but to design test methods that replicate the effects of the essential environmental stresses on the product. The challenge with tailored test methods is that in the absence of strict guidelines more time, effort, and experience may be required from the test personnel. In addition, the interpretation of the results may be more complicated and harder to compare to other test methods. [Bho04][Sal08]

2.3.1 Reliability testing methods

Different kinds of reliability testing methods can be utilized depending on what sort of results or reliability data is required. In this chapter a few commonly used test methods such as screening tests, accelerated life tests, and highly accelerated life tests (HALT) are briefly discussed.

Screening tests

Screening tests can be used before products are shipped to customers in order to identify items with latent defects that cannot otherwise be detected through visual inspection or electrical testing. By eliminating the defective units infant mortality failures in use conditions may be minimized. Burn-in is one of the oldest but a still used screening test method that utilizes elevated temperature to weed out defective items. However, elevated temperature alone is not considered an efficient method to detect hidden flaws in a short period of time without a significant effect on the useful life of the products [Jen95][Lal97]. Therefore combinations of elevated temperature and electrical stress have also been used. However, thermal cycling may, in many cases, be a more effective screening method for the detection of e.g. mechanical damage, broken bonds, and broken contact pins in electronic components. Nevertheless, burn-in testing of all manufactured products may significantly increase the manufacturing process time, which otherwise needs to be minimized. [Lal97][Oco05]

Accelerated life testing

In the case of quantitative reliability testing, the accelerated test methods are based on the assumption that the lifetime of a product is limited by a known failure mechanism, which does not change during testing. The objective is therefore to extrapolate the results from the accelerated tests to a specific use condition. In order to do so, an acceleration factor (AF) is needed between the test environment and the actual use conditions. By definition, AF can be defined:

$$AF = \frac{Time\text{-}to\text{-}failure\ at\ use\ condition}{Time\text{-}to\text{-}failure\ at\ test\ condition} \tag{4}$$

Quantitative reliability testing in normal use conditions is often impossible due to time constraints. However, the AF may be determined by performing accelerated tests at varying elevated stress levels and then fitting an acceleration model to the test data, which can relate the stress level used to time acceleration. Various acceleration models have been developed for different failure mechanisms and environmental stresses. These include temperature, voltage, humidity, corrosion, cyclic fatigue, creep, and electromigration. The selection of the right acceleration model depends on the product to be tested, the test method used, and on the knowledge of the particular failure mechanism. This method is also known as the physics-of-failure approach as it is based on the root cause analysis of observed failures and on the understanding of the relevant failure mechanisms. [Esc06][Sal08][Vis98]

As an example, the Arrhenius model has been widely used to derive acceleration factors for temperature related failure mechanisms in electronic components such as corrosion and diffusion [Jen95][Den06]. This model is based on chemical reaction rates at specified temperatures and with specific activation energy (E_a). The Arrhenius AF is shown in Equation 5. In the equation, k is the Boltzmann's constant ($8.617 \cdot 10^{-5}$ eV/K) and T_{use} and T_{test} are the absolute temperatures in use and test conditions in degrees Kelvin. The parameter E_a depends on the particular failure mechanism affecting the lifetime of the tested product and normally varies between 0.3-1.2 eV. [Esc06][IEE02][Lal97]

$$\textit{Arrhenius AF} = e^{\left[\left(\frac{E_a}{k}\right)\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right]} \tag{5}$$

Humidity is also an important environmental stress factor and therefore electronics is commonly tested using both elevated temperature and humidity. Peck's model, which was developed for semiconductor components in epoxy packages, incorporates the Arrhenius model with a power law for humidity. The AF for the Peck's model is shown in Equation 6. In the equation, n is a material constant and M_{use} and M_{test} are the relative humidity percentage values in use and test conditions. [IEE02][Pec86][Den06]

$$\textit{Peck's model AF} = \left(\frac{M_{use}}{M_{test}}\right)^{-n} e^{\left[\left(\frac{E_a}{k}\right)\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right]} \tag{6}$$

Temperature changes due to ambient conditions or internal heating are also a significant factor affecting the reliability of electronics. The use of a number of different materials with differing coefficient of thermal expansion (CTE) values gives rise to fatigue failures of solders and polymers. Consequently, temperature cycling is an often used accelerated testing method. A commonly used model in the prediction of fatigue failures under thermal cycling is the Coffin-Manson relationship. The model states that the number of cycles to failure with a given material is inversely proportional to the temperature range used. The derived AF for the model is shown in Equation 7. The N_{use} and N_{test} are the cycles to failure values in use and test conditions, the ΔT_{use} and ΔT_{test} are the temperature cycling ranges in use and test conditions, and m is an empirically determined constant. [Esc06][IPC92][IEE02]

$$\textit{Coffin-Manson AF} = \frac{N_{use}}{N_{test}} = \left(\frac{\Delta T_{test}}{\Delta T_{use}}\right)^{m} \tag{7}$$

The acceleration models and the corresponding AFs are only valid between specified limits and if the failure mechanism modelled remains unchanged [Jen95]. If too high an acceleration is used, i.e. if the stress level or the usage rate is too high, the risk of inducing a wrong failure mechanism increases. This may cause the product to fail in a way not inherent in the actual service conditions. This, in turn, may result in erroneous conclusions about the reliability of the product. An indication of a changed failure mechanism is typically when a change is observed in the parameters of the statistical distribution used. That is, in the case of the Weibull distribution a marked change in the shape parameter β may indicate a change in the failure mechanisms between two tests with differing stress levels.

Highly accelerated life testing

Highly accelerated life testing (HALT) is a test method that can be applied during the design phase to reveal and correct the weakest links that affect the reliability of a product. This method uses step-stress testing and stress levels markedly higher than those observed in normal use conditions. HALT does not simulate the actual service environment [Oco05]. The aim is to induce failures as quickly as possible which are then analysed and documented. After the root cause for a failure has been discovered the failure is fixed by improving the design and the testing is continued to find out what is the next weakest link. HALT is usually continued until the operational and destruct limits have been discovered with each stress used. The advantage of this testing method is that products can be made more robust by eliminating the weakest links early on during the design process. Therefore, the reliability in use conditions may be improved and warranty costs reduced. However, because the number of samples available for HALT during the design phase is usually limited, the statistical analysis of the results may be difficult. Furthermore, contrary to the name, HALT cannot be used as a life estimation or prediction method. [Bho04] [Oco05][Por04]

2.3.2 Reliability testing stress levels and test hierarchy

When accelerated reliability testing is performed the stress levels used may be set above the specification limits but well below the destruct limits of a product. Testing should also be performed at different stress levels and using several different stressors in order to avoid problems and erroneous conclusions in the interpretation of the results [Mee98]. That is, if a product is only tested at a single elevated stress level the severity and importance of the observed failure modes may be masked. In other words, even though in the high stress test conditions one failure mode seems to be more critical than the others, in reality some other failure mode may be more relevant in conditions of normal use. [Mee98]

Reliability testing can be conducted at different hierarchical levels. In this work the lowest level of testing is defined to comprise an individual component or its electrical joints. Alternatively, higher level testing may include a number of separate components that are part of the same functional block or subsystem. In turn, system level testing comprises a number of differing sub-systems that together may form a complete device. The lower-level testing of individual components or small sub-assemblies is usually more economical, easier to perform, and enables the use of greater number of samples. In addition, testing at this level can often be performed earlier during the design phase of a product than at system level [Oco05]. Furthermore, at component level, the number of failure modes and mechanisms likely to affect a particular component type and model during operation is fairly limited.

Instead, as the number of components in an assembly increases, so does the overall number of possible failure modes and mechanisms. This, in turn, may complicate the interpretation and statistical analysis of test results. Nevertheless, component level tests results should not be used as the only method to determine the overall system reliability of a product because of possible interaction effects between components and subsystems. Therefore system level testing is essential even if it is more challenging. [Oco05]

2.3.3 Multiple stresses

As mentioned, products may be subjected to a number of environmental stresses during their service life. From the reliability testing point of view, the application of a single stress during an accelerated lifetime test is more straightforward and typically enables easier interpretation of test results. Single stress test methods may also be used consecutively in order to study how pre-aging in some specific environmental condition affects the reliability of a product during a subsequent test. For example, thermal cycling or vibration testing may be used to induce cracking in a product, which might accelerate failures during an elevated temperature and humidity test. However, a challenge with this kind of testing is that environmental stresses rarely occur alone or consecutively in service conditions and often their combined effect may be substantially more severe than their individual effects. Therefore the specific stresses applicable for the actual operating conditions of a particular product should also be applied simultaneously during reliability testing. This makes it possible to study the interaction effects of various stress factors. Consequently the reliability test may be improved and made to better represent the real use environment and the potential reliability risks. [Mar99][Kly06][Oco05]

Cumulative damage models are needed to predict the lifetime of electronic products in conditions with multiple stresses. These models are used to estimate how much differing stresses with different stress levels will consume the overall lifetime of a product. Currently, the majority of electronics failures are related to thermo-mechanical stresses, especially in the case of microelectronic components [Wun06]. Therefore cumulative damage models based on fatigue failures of metals and solders have commanded a lot of attention [Fat98]. One of the first and still commonly used linear damage models is the Palmgren-Miner rule. The rule states that the accumulated fatigue damage at given stress levels can be calculated as fractions of the overall fatigue life and summed up. The mathematical form of the rule is shown in Equation 8. In the equation, n_i is the number of cycles applied at a given stress level and N_i is the cycles-to-failure at that same stress level. A fatigue failure will occur when the sum of the fractions equals unity.

$$\text{Fatigue damage} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots = \sum \frac{n_i}{N_i} \tag{8}$$

The Palmgren-Miner cumulative damage model can therefore be used to combine the fatigue effects of, e.g. mechanical shocks, thermal cycling, and vibration. However, the rule is only applicable if the different loading histories actually are linearly cumulative, the order in which the loadings occur does not matter and there are no interaction effects between stresses

[Fat98][IPC92]. A number of other cumulative damage models have been developed that take account of other relevant factors. These models include energy based, crack growth, or non-linear superposition methods. However, their applicability has been observed to vary from case to case and none of the models can take into account all the possible factors affecting the fatigue life of solder joints [Fat98]. Therefore, thanks to its simplicity, the Palmgren-Miner rule is still commonly used.

At present multiple stress testing is not commonly utilized due to its complexity and lack of specific standard testing procedures. Not only can it be difficult to determine and quantify the numerous stresses affecting the lifetime of a product at a specific location, but the analysis may be further complicated if a product is also used in different environments. In addition, the application of multiple stresses may quickly become impractical and costly because of the testing equipment requirements. In some cases actual service condition stresses cannot be reproduced realistically or reliably during laboratory testing [Dep08]. The statistical analysis of test results may also become challenging if the stressors used activate a number of different failure mechanisms that cause a product to fail with differing failure modes. This may be especially problematic during the system level testing of complex devices. Furthermore, not enough is known about how failure mechanisms interact and how to combine multiple stresses in order to replicate and accelerate use conditions [Mat11a][Nel04][Qi08].

3 INTERCONNECTION LEVEL RELIABILITY TESTING: FLEX-ON-BOARD ATTACHMENTS

Surface mount technology (SMT) is currently in common use with electronic components as it enables system size reduction, enhanced electrical performance and the use of package types with higher number of inputs/outputs (I/O). Due to this, the interconnections between components and printed circuit boards have also become a critical part of the overall reliability of an assembly [Har97]. This is because the interconnection provides a component not only with electrical connectivity but also mechanical stability.

3.1 FLEXIBLE CIRCUITS

Printed circuit boards (PCB) are one of the main elements of electronics. Their main function is to provide electrical connectivity and mechanical support for components [Har97]. Flexible circuits are a subset of PCBs that are manufactured on a thin and flexible base material [Har00]. The core of a flexible circuit is usually non-reinforced polymeric material, which enables them to be used in applications that are susceptible to bending. They can also be used to save space and weight compared to conventional insulated wires and cables. The structure of a flexible circuit can vary from single or double-sided to complex multilayer circuits with through-holes and inner via holes [Coo01][Jaw97]. Similarly to rigid PCBs flexible circuits are used to connect individual components but they can also be used as connectors between different systems and assemblies [Har97]. Advantages of using thin and pliable flexible circuits also include improved reliability of interconnections as the mechanical stresses caused by temperature changes can be reduced [Fri09][Suh91]. At present, flexible circuits are widely used in products that range from commercial and industrial to medical and military applications [Fje97][Har00][Ste96]. These applications include e.g. cameras, hard disk drives, calculators, mobile phones and notebook computers [Coo01][Jaw97].

3.1.1 Materials

The requirements for a base dielectric material to be used in flexible circuits include high tensile strength and modulus, high melting point, high glass transition temperature (T_g), low CTE, and good thermal stability [Har00]. Various materials have been employed in flexible circuits including fluorocarbons, polyimides (PI), polyethylene terephthalate (PET), polyethylene naphthalate (PEN), liquid crystal polymers (LCP) and thin glass-epoxy, but the two most common materials used are PI and PET [Coo01]. PI has good overall physical properties for flexible circuit use but the main advantage is its ability to withstand high-temperature processes such as soldering. The disadvantages of PI include relatively high moisture absorption and cost. PET on the other hand is cost-effective and in addition to low moisture absorption it has an excellent mechanical performance at room temperature. However, PET has low T_g and it is not suitable for conventional soldering. [Cal07][Mat12]

In addition to the core dielectric material, flexible circuits incorporate conductors that can be manufactured from various materials and using methods based on the requirements of the application. The most commonly used conductor material is copper [Har00]. Copper-clad laminates are typically manufactured by attaching a copper foil to the base material with acrylic or epoxy adhesive and laminating the structure by using a specific temperature and pressure. The downside of this method is that the properties of the adhesive resin used greatly affect the overall performance of the flexible circuit. Poor heat and moisture resistance of the adhesive resin can be especially problematic [Coo01][Har00]. Because of this laminates without an adhesive layer have been developed specifically for applications requiring high density interconnects. Other conductor materials that can be used in flexible circuits include aluminium, nickel, gold and carbon [Coo01].

3.1.2 Attachment methods

Flexible circuits have been used as an interface between a rigid circuit board and a connector or connection in applications where traditional wiring could not be accommodated [Jaw97]. Depending on the application, design and materials used, the flexible circuit can be connected by reflow or hot bar soldering, with anisotropically conductive adhesives (ACA), or with socket type connectors [Kim07]. Soldering requires the flexible circuit to endure high temperatures, which limits the number of usable dielectric materials. Socket type connectors increase overall expenses compared to direct attachment methods and they are not always practicable for high density applications but they enable easy reparability. Alternatively ACAs provide ultra-high density interconnections in addition to facilitating the usage of temperature sensitive low cost materials such as PET. [Li06][Lic05] However, they require special manufacturing equipment and the attachments can be very difficult to repair. This work will focus solely on the usage of ACA attaching methods.

3.2 ANISOTROPICALLY CONDUCTIVE ADHESIVES

Adhesives are currently an important part of the assembly and packaging process of electronic devices. Depending on the material properties they can be used to mechanically bond differing materials together, to create electrical connections, and to dissipate heat and stresses [Lic05]. In order to conduct electricity, adhesives require the addition of conductive particles as the polymer resins commonly used as matrix material are non-conductive [Lic05][Lu10]. Depending on the amount of added conductive filler material the adhesive can be classified as isotropic or anisotropic. The difference between the two is that with isotropically conductive adhesives (ICA) the volume fraction of the filler material is so high (25-30 %) that the adhesive starts to conduct equally in all directions. [Lic05][Lu10] The conductive filler level where this happens is called the percolation threshold. With ACAs the volume fraction of the conductive particles is substantially lower, from 0.5 % to 10 %, which means that the particles are not in direct contact with each other and the adhesive remains non-conductive. However, during bonding the particles caught between the contact bumps and pads enable electrical conductivity through the z-axis. Because the filler particles do not form continuous conductive paths on the x-y plane, ACAs can be used in small pitch attachments without inducing a short circuit between adjacent contact pads. [Lu10][Riz05]

Because the advantages of using ACAs include fine-pitch capability, simple processing, low processing temperatures and no underfilling, they have seen widespread use in liquid crystal display (LCD) modules, cell phones, radios, laptop PCs and cameras. [Jia05][Kri98][Li10][Mat07][Mor07]

3.2.1 Materials

The two main components of an ACA are the polymer matrix, which holds the assembly mechanically together, and the conductive particles, which enable electrical conductivity after curing. Both thermoplastic and thermoset polymers are used with ACAs. Thermoplastic polymers, such as polyamides and acrylics, exhibit a linear molecular structure after hardening, which allows them to be melted and solidified with the application of heat. This facilitates the reworking of ACA interconnections. However, ACAs based on thermoset polymers are more commonly used due to their good overall properties, which include high adhesive strength, high T_g, good chemical and corrosion resistance, and high temperature endurance. They also exhibit better mechanical properties compared to thermoplastic polymers, which creep under load. These adhesives include epoxies, silicones and cyanate esters. When cured the molecular structure of thermoset polymers becomes cross-linked. This curing reaction is not reversible, the adhesive therefore does not melt but instead decomposes and chars with high enough temperatures. [Lic05][Lin08a]

A wide range of conductive particle choices are available for ACAs, but the selection of the particle material, size and concentration should be based on the specifications of the application. Typical materials used in conductive particles include gold, silver, copper and nickel. From these a common particle choice is nickel with or without a gold coating, which can be used to prevent the surface of the particle from being oxidized. Nickel particles are hard and can therefore be used to penetrate oxidized contact pad metallization such as aluminium during bonding. In contrast to rigid particles, polymer spheres with nickel or gold plating are also widely used. Because of the soft polymer core, these particles deform more easily during bonding and therefore the contact area between the particles and the contact pads can be increased. The size of the conductive particles used in ACAs ranges typically from 3 to 10 μm. As the electrical conductivity of an ACA joint depends on the number of conductive particles caught between the contact pads or bumps, the overall resistivity can be decreased by increasing the particle concentration. With high particle concentrations an insulation layer can be used on top of the conductive particles in order to decrease the risk of a short circuit between contacts.

The material properties of an ACA can be modified by mixing electrically insulating filler material into the polymer matrix [Lic05]. In order not to impair the conductivity of the adhesive, the size of the filler material needs to be smaller than that of the conductive particles. By adding non-conductive filler such as silica, alumina, aluminium nitride, or boron nitride the thermal conductivity of the adhesive can be increased and the thermal stability improved. In addition, adding filler material typically lowers the CTE and increases the Young's modulus of the adhesive. However, an increase in the Young's modulus makes the adhesive more rigid and therefore it may cause higher stresses to be induced in joints during temperature changes [Lic05][Suh91]. Furthermore, an increase in the Young's modulus may decrease the adhesion strength of the adhesive [Fri06][Nag98].

3.2.2 Bonding process and the effect of bonding parameters

The first step in the bonding process of ACAs is the application of the adhesive to the bonding area, which should be cleaned beforehand. The application method of the ACA depends on whether a paste or film form is used. Pastes can be stencil or screen printed or alternatively syringe dispensed onto the substrate. Film form adhesives are instead supplied in reels from which a piece of the right size is cut and placed onto the bonding area. A pre-bonding step is required to fasten the film to the substrate during which the adhesive is lightly pressed and heated for a short period of time. In order to facilitate handling the film form adhesive includes a carrier tape, which needs to be removed before final bonding.

The application of the adhesive is followed by the alignment step, where the contact pads of the two surfaces to be attached are positioned on top of each other. With the application of pressure the two surfaces are then brought into contact during which excess adhesive is pushed aside and some of the conductive particles are trapped between the contact pads. The polymer matrix is then cured by applying heat to the adhesive while maintaining a constant bonding pressure. After a specific curing time the assembly is cooled down below the adhesive's T_g before the pressure is lowered. [Mie98] This is done to ensure that a sufficient contractive force is generated inside the joint, which is a requirement for a stable electrical connection. [Chu10]

The three most important bonding parameters are pressure, temperature and time. The selection of the right values for these process parameters is critical to the overall performance of the adhesive joints. However, this is not always straightforward because the properties and the materials of the whole assembly can also have a significant effect on the result. In the case of bonding pressure the applicable value needs to be calculated according to the requirements of the adhesive manufacturer and the specifications of the components and substrates to be attached. With too low a pressure the contact resistance of the joint can end up being too high because the conductive particles are not in good enough contact with the contact pads or the particles have not deformed adequately [Tao10]. Additionally, the risk of open contacts increases. On the other hand, excessive bonding pressure may inflict too high mechanical stresses that may compromise the reliability of the joint, distort the structure, or even break the chip or the substrate [Che06][Fri09]. Furthermore, high pressure may cause the conductive particles to be crushed, e.g. in the case of soft polymer particles, or to sink inside the contact pads if hard particle material such as nickel is used with copper or gold bumps. In both cases the conductive particles are no longer able to compensate the mechanical stresses caused by temperature fluctuations and CTE differences between materials, which in turn may cause the formation of open circuits.

The temperature used during bonding will affect the curing degree and the mechanical properties of the adhesive as well as the overall process time. With the application of heat the polymer matrix of an adhesive first softens allowing it to flow through the joint area, which helps to distribute the conductive particles evenly. Gradually the curing process proceeds through polymerization and crosslinking reactions that transform the adhesive to a solid. If the bonding temperature used is too low or the curing time too short, the state of cure of the adhesive may be inadequate. This in turn will affect the mechanical and chemical properties, such as T_g, Young's modulus, and tensile strength, of the adhesive and therefore also the reliability of the assembly [Lap02][Mou12]. By using a high bonding temperature the process time can be kept to a minimum, which is often preferred. However, when the temperature is increased the flow time of the adhesive is reduced and the polymer matrix may be cured too abruptly. High residual stresses may also be formed in the joints because of the combined effect of high temperature and CTE differences between materials. The temperature sensitivity of the assembly materials also needs to be taken into consideration when the bonding temperature is selected [Yim06].

3.3 TEST SAMPLES

The interconnect level testing conducted in this work comprised ACA attached flex-on-board (FOB) samples. In Publication I self-made FOB assemblies were tested in order to vary the process parameters. In Publications II and III prefabricated test samples were used.

The test samples used in Publication I comprised PET flexes that were attached to FR-4 PCB using commercially available anisotropically conductive film (ACF) designed for low temperature applications. The ACF was an acrylic-based polymer and its rigid conductive particles were gold-coated nickel. The flex used had a three-layer structure consisting of a PET base material, an adhesive layer, and a copper conductor layer with tin coating. The substrate used was a single-sided FR-4 with nickel/gold-coated copper traces. The contact area of the FOB attachment comprised 150 contact pads with a pitch of 200 µm, which formed a daisy chain structure. A complete FOB assembly is shown in Figure 3. The test batches and the used bonding parameters are listed in Table 2.

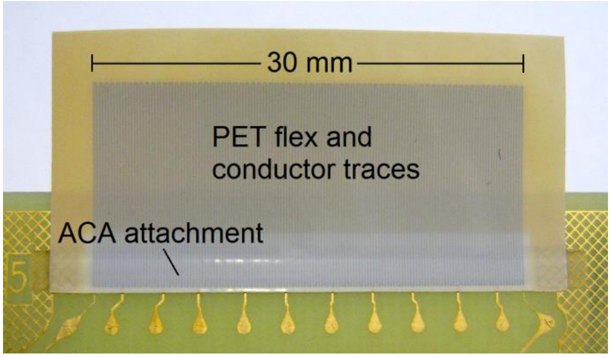

Figure 3: FOB attachment tested in Publication I.

Table 2: Bonding parameters and number of samples used in Publication I.

Test Batch:	Thermode Temperature:	Measured Temperature:	Time:	Pressure:	No. of Samples:
A1	170 ˚C	120 ˚C	30 s	7 MPa	10
A2	170 ˚C	120 ˚C	60 s	7 MPa	10
A3	170 ˚C	120 ˚C	90 s	7 MPa	10
B1	200 ˚C	140 ˚C	30 s	7 MPa	11
B2	200 ˚C	140 ˚C	60 s	7 MPa	10
C1	220 ˚C	160 ˚C	30 s	7 MPa	11
C2	220 ˚C	160 ˚C	60 s	7 MPa	12

In Publications II and III the FOB attachment of an LCD card was used as a test specimen. The LCD card was part of a user interface device used to control the operation of a frequency converter. The card comprised an LCD panel which was connected to a PCB substrate with a flexible circuit. The base material of the flex was PET and it contained 32 stencil printed conductor traces. The flex was attached to both the LCD panel and the PCB with ACA, but only the FOB attachment between the flex and the PCB was studied. A photograph of the FOB attachment is shown in Figure 4. In the picture the LCD panel has been removed in order to facilitate real-time measurement during testing. The contact pads of the FOB attachment on the PCB side were nickel and gold coated copper. The pitch of the FOB attachment on the PCB side was 800 µm. The ACA contained metal coated polymer particles and it was first pre-bonded in film form to the PET flex before its actual bonding to the PCB.

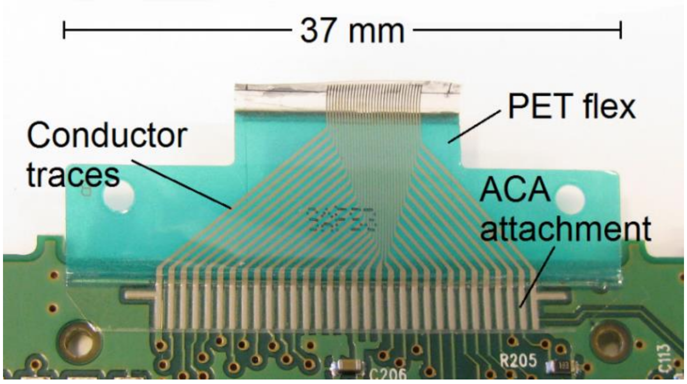

Figure 4: FOB assembly of the tested in Publication II and III.

3.4 TEST EVALUATION METHODS

In order to evaluate how the performance of a product is affected by a specific test, a monitoring method is required. To enable this, a characteristic signal specific to the operation of the specimen needs to be observed. The monitoring can be realized with constant measurement during testing or periodically between tests. Additionally, a criterion for a failure needs to be determined. Although a failure is commonly understood as an occurrence after which a product is no longer able to perform its required function, the selection of a failure criterion can be quite complicated [Jen95][Ohr98]. In-depth knowledge about the test specimen, use environment and testing method may be required in order to differentiate a degraded performance from an actual failure.

3.4.1 Resistance

In the case of reliability testing at interconnect level the electrical properties of the joints are of great importance. Therefore the measurement of resistance and the detection of electrical discontinuities are commonly used to evaluate the performance of various kinds of interconnections [Tum97a]. However, numerous failure definitions and criteria have been used in different studies, which in the worst case may complicate the comparison of test results. Furthermore, different resistance measurement methods can also be used. These include measurements performed at set intervals between tests, monitoring for a specific resistance increase during testing with a data logger, or using equipment capable of detecting extremely short electrical discontinuities [IPC92]. Guidelines and specifications are available that provide standardized testing methods and procedures. For example IPC-SM-785 and IPC-9701A are widely used in the testing of surface mount solder attachments [IPC92][IPC02]. These documents state that measurements that are conducted at set intervals at ambient conditions are not an accepted evaluation method during temperature cycling testing. This is because they cannot be used to detect initial failures at temperature extremes or during temperature changes. In addition, the accuracy of this method depends on the sampling frequency, which in turn disrupts testing and causes delays. Instead, a continuous electrical monitoring of the samples is required, either using an event detector with a high-speed data acquisition capability or a data logger. Because the duration of the initial resistance spikes preceding a failure in a solder joint usually are very short-term, a high-speed event detector is preferred [IPC02].

The failure criterion defined by the standards depends on the monitoring method used. With an event detector a failure is defined as the first occurrence where the resistance of a sample exceeds 1 000 Ω for a period of 1 μs or less. In addition, at least nine similar subsequent failure events are required within 10 % of the cycles to the initial failure to verify that the incident was not caused by test equipment or software malfunctions [IPC92][IPC02]. In the case of a data logger, a failure is defined as a maximum 20 % increase in the initial resistance, which is verified with a maximum of five consecutive readings [IPC02].

In this work a real-time measurement system was used to monitor the resistance of FOB samples in Publications II and III. The data acquisition system comprised a data logger with separate channels used to measure voltages in reference to ground potential. Each channel contained two measurement wires: a wire used to measure voltage and a ground signal wire. Each voltage measurement wire also included a 1 000 Ω pull-up resistor (R_{Ref}) in series with a 5 V direct current (DC) power supply (V_{S}). A circuit diagram of the used measurement setup is shown in Figure 5. The measured voltage of a sample could then be converted to a resistance value with the Equation:

$$R_{\mathrm{Sample}} = \frac{V_{\mathrm{Sample}} \times R_{\mathrm{Ref}}}{V_{\mathrm{S}} - V_{\mathrm{Sample}}} \tag{9}$$

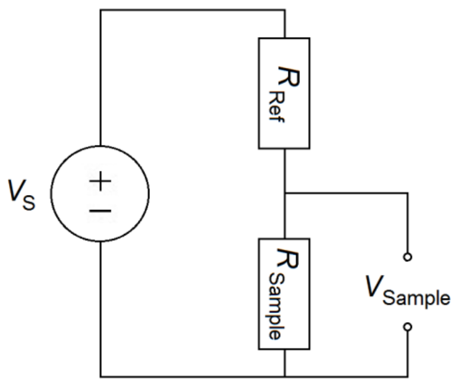

Figure 5: Voltage measurement circuit schematic.

In Publications II and III the real-time resistance measurement was realized by first detaching the PET flex from the LCD panel. A ground signal wire was then attached to the end of the flex with ICA. Afterwards eight measurement channels from the data logger were soldered to vias located below the ACA attachment on the PCB. Due to the test setup, the resistance measured by the data logger included not only the ACF joint resistance but also the resistance of the ICA attachment and the conductor traces on the flex. The voltage measurement interval used during testing was 10 seconds. A fivefold increase in the sample resistance was used as the failure criterion. This criterion was selected on the basis of the requirements of the FOB assembly. That is, compared to the initial value a resistance increase of 10 or 20 % would not affect the functionality of the display device. Even a fivefold increase in the resistance of the adhesive joints would not be critical for the operation of the device. However, this was considered to be a practical value for the detection of conductivity failures. In order to ensure that the observed failure was not caused by electrical interference or a system malfunction, five succeeding measurements exceeding the failure criterion were used as verification.

3.4.2 Adhesion

In addition to electrical conductivity, other test evaluation methods can also be used. For example, mechanical strength is also a critical factor for the reliability of an adhesive joint. Therefore measuring the changes in adhesion strength has also been widely used to evaluate the stability of adhesive attachments under environmental stresses. [Lic05]

In this work the effects of bonding parameters as well as the impact of environmental stress tests on the mechanical strength of FOB attachments were studied. In Publication I differing curing temperatures and cure times were used to manufacture FOB samples that were then subjected to a 90-degree peel strength test in order to compare their mechanical strength. In Publication II FOB samples were aged using a temperature cycling test and the change in the samples' mechanical strength was studied by performing peel tests at set intervals. In Publication III constant temperature and humidity tests and a humidity cycling test were used to age samples before subjecting them to the same peel strength test.

The adhesion testing conducted in this work was performed by using a 90-degree peel strength test, which can be used to evaluate the adhesion properties of films in electronic applications [Rab06]. The test was based on standard ASTM D6862-04 [AST04]. The measurement device used was a Nordson Dage series 4 000 bond tester. An illustration of the peel strength test setup is shown in Figure 6. The FOB samples were attached to a mounting table in upright position. An aluminium clamp was attached to the flex and connected to the tool head of the measurement device. The force exerted on the measurement tool was measured as a function of peel distance until the complete failure of the adhesive attachment.

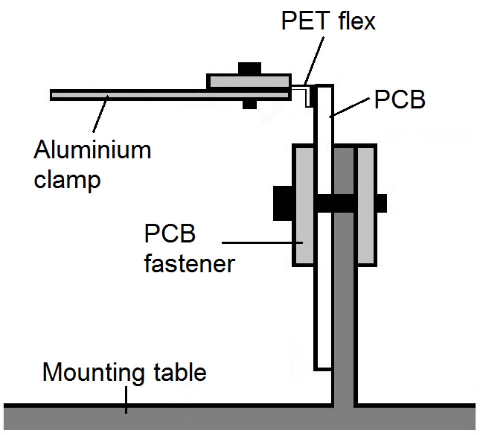

Figure 6: 90-degree peel strength test set up.

3.5 RELIABILITY TESTS

Varying environmental stress tests are commonly used in order to assess a product's reliability within its lifetime under some specified operating conditions [Jen95][Tum97a]. In many cases the reason behind a product malfunction is a degraded interconnection at a specific packaging level or between connectors [Tum97a][Ohr98]. The selection of a reliability test method depends largely on the product itself and on the environmental factors affecting the service conditions. With adhesive attachments many environmental stresses such as elevated temperatures, thermal cycling, humidity, and mechanical impacts can have a significant effect on the overall reliability [Lin08b]. Therefore, different test methods are required in order to study different failure mechanisms. In this work temperature cycling tests and temperature-humidity tests were used.

3.5.1 Temperature cycling tests

Due to differing CTE values between materials, fluctuating temperature induces mechanical stresses in products during use. Temperature cycling is therefore a commonly used test method for studying the reliability of electronics. In the case of adhesive attachments a number of test methods with varying soak temperatures, temperature change rates, and soak times have been used [Ali05][Fri05][Gao12][Saa11a]. However, a clear understanding of the effects of these test parameters on the test results and the testing time is still lacking.

The temperature cycling test performed on the FOB samples in Publication II was based on JEDEC's JESD22-A104D standard [JED09b]. The low and high temperature limits used were -40 °C and 125 °C respectively. The soak times used were five and 14 minutes. With both soak times the transition time between the high and low temperature was one minute, thus a complete cycle lasted 12 or 30 minutes. The duration of both of the tests was 10 000 cycles.

3.5.2 Constant temperature and humidity tests

Adhesive attachments are commonly used in applications in which they are subjected to humid environments. Moisture may cause differing adverse effects to adhesive joints degrading their properties and therefore hygrothermal stress is considered a critical factor affecting the operating life of adhesive attachments. [Jan10][Lin06][Mub09]

Two test methods with constant temperature and humidity were used in Publication III to study the reliability of FOB samples. The first test was based on IPC's standard IPC-TM-650 number 2.6.3.1E [IPC07] with constant test conditions of 65 °C and 90 %RH (65/90). The test was performed in 500-hour test runs between which the temperature and humidity were lowered to ambient conditions. The overall length of the test was 5000 hours. The second test method was also a constant temperature/humidity test based on JEDEC's JESD22-A101C standard [JED09a]. The test temperature was 85 °C and the relative humidity 85 %RH (85/85). The test was similarly performed in sets of 500-hour testing periods and the total duration was 3500 hours.

3.5.3 Temperature and humidity cycling tests

In contrast to the constant temperature and humidity tests, a high humidity temperature cycling test and a humidity cycling test were also conducted on FOB samples and reported in Publication III. In the first test method the RH was held at 90 % while the temperature was cycled between 10-65 °C. This was done in order to induce moisture condensation on the samples. The temperature and humidity profile from the period of three test cycles is shown in Figure 7. The cycling test was started by lowering the temperature to 10 °C and increasing the RH to 90 %. After a 20-minute soak time the temperature was raised to 65 °C within 20 minutes during which time moisture would condense on top of the samples. The temperature and RH humidity were then kept constant at 65 °C and 90 % respectively for 60 minutes before the temperature was lowered back to 10 °C within 40 minutes. Then, after a 30-minute soak at 10 °C / 90%RH a new cycle would be started by increasing the temperature to 65 °C within 20 minutes. The duration of one cycle was 150 minutes. After a set of 25 cycles the temperature and humidity inside the chamber were lowered to room conditions for 30 minutes before the test was continued.

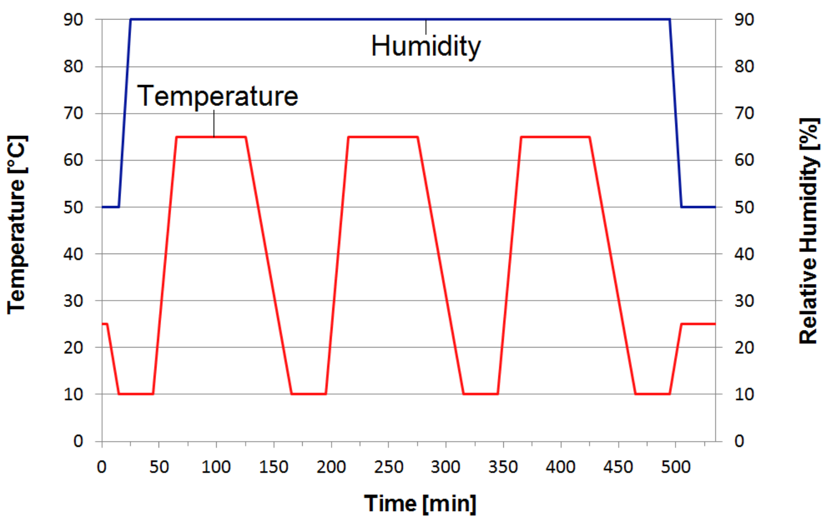

Figure 7: 65/90 cycling test profile.

In the second test method the relative humidity was alternated between 10 and 85 % while a constant temperature of 85 °C was maintained. The duration of one test cycle was eight hours. At the start of a cycle the temperature was first raised and kept at 85 °C for one hour before the relative humidity was increased to 85 %. After two hours the relative humidity was lowered to 10 % while maintaining a constant temperature. After drying the sample for two hours, the temperature and humidity were returned to ambient levels before the start of a new cycle. The test was continued for 882 cycles or 7056 hours, in total. A profile of the test conditions is shown in Figure 8.

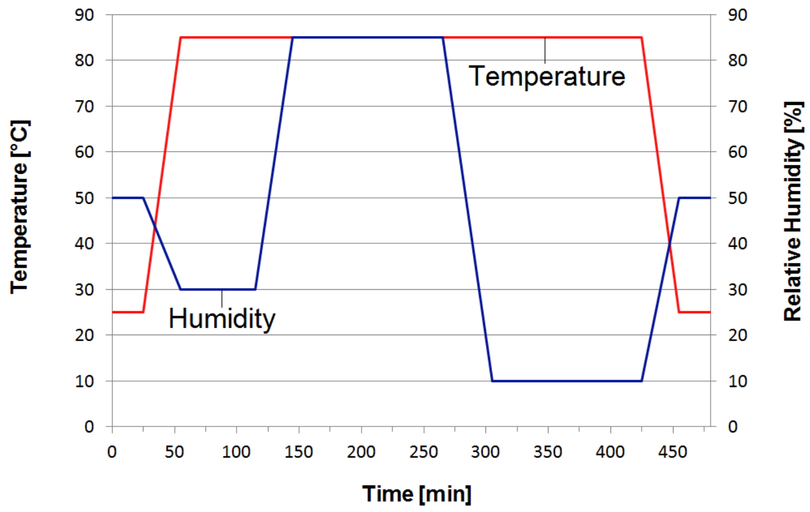

Figure 8: 85/85 cycling test profile.

3.6 EFFECT OF BONDING TEMPERATURE AND CURING TIME

The effect of bonding process parameters on the mechanical strength of an adhesive attachment was studied in this work. The results of this study are presented in this chapter. FOB samples were first manufactured by using three different curing temperatures with two or three different curing times. The mechanical strength of the assemblies was then examined with a 90-degree peel strength test. A more detailed description of this research can be found in Publication I.

3.6.1 Peel test results

The average and maximum forces were calculated from the peel test data, likewise their standard deviations. The results are shown in Table 3. As can be seen, for the 120 ºC and 160 ºC curing temperatures the average force and the average maximum force values were observed to increase between the 30-second and 60-second curing times. However, for the 120 ºC curing temperature both values were then observed to decrease slightly with the longest cure time of 90 seconds. Additionally, for the 140 ºC curing time the average force and the average maximum force values remained almost the same with both curing times used. The standard deviation values of test batches A, B and C were observed to increase when the curing time was increased.

Table 3: 90-degree peel strength test results.

Test Batch	Average force: (N)	Standard deviation:	Average maximum force: (N)	Standard deviation:
A1 (120 ˚C, 30 s.)	34.8	1.1	51.1	2.0
A2 (120 ˚C, 60 s.)	40.6	2.9	55.3	3.7
A3 (120 ˚C, 90 s.)	38.4	4.3	52.5	6.0
B1 (140 ˚C, 30 s.)	44.2	2.6	58.5	3.9
B2 (140 ˚C, 60 s.)	43.6	3.0	58.7	5.0
C1 (160 ˚C, 30 s.)	46.4	2.5	61.3	3.7
C2 (160 ˚C, 60 s.)	53.1	3.4	76.4	7.8

The results indicated that the cure temperature had a more significant effect on the mechanical strength of the assembly than the curing time. With the lowest bonding temperature used (samples A1-A3) the increase in the curing time did indeed improve the peel strength results but only slightly. In addition, the standard deviation of the results was also observed to increase with the curing time. Instead, the use of 20 °C higher cure temperature (samples B1 and B2) resulted in better peel test results. Again, the longer curing time did not improve the results and only the standard deviation was observed to increase slightly. The best mechanical strength was obtained with the highest cure temperature used. In this case the use of longer curing time also resulted in improved peel test results, which was not observed in the samples with lower cure temperatures. However, the longer curing time again increased the standard deviation of the samples.

The cure temperature during bonding and the resulting adhesive degree of cure has a significant effect on the mechanical properties of an adhesive assembly and therefore peel strength can be enhanced by using a higher bonding temperature [Cao04][Udd04][Lin07]. However, using a longer curing time should also have a similar effect, which was not clearly observed in this study [Yu06][Chu10]. In other words, the curing of the adhesive seemed to be more temperature restrained, especially when low bonding temperatures were used.

3.6.2 Degree of cure

To understand the effect of the curing properties of the adhesive used in this research it was studied using differential scanning calorimetry (DSC). During curing the cross-linking reactions of the polymer material generate heat, which can be detected with DSC. The DSC result illustrating the heat flow of the adhesive during curing is shown in Figure 9. An exothermic peak was observed in the DSC curve at a temperature of 121 °C. Consequently, the adhesive should start to cure even at a curing temperature of 120 °C. Isothermal DSC tests conducted at temperatures of 120, 140 and 160 °C, showed that the lowering of the curing temperature caused the curing time to increase.

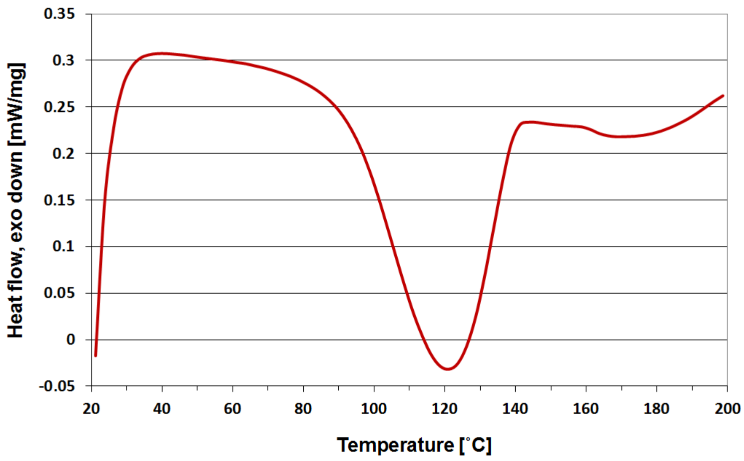

Figure 9: DSC curve of the adhesive.

The curing degree of the adhesive was also studied by DSC. The results are shown in Figure 10. A high degree of cure is preferable in an adhesive joint as this not only increases the cohesive strength but also improves the interfacial adhesion strength [Cao04][Chu10][Udd04]. As can be seen from Figure 10, the cure temperature used had a significant effect on the curing degree of the adhesive. In order to ensure good adhesion, low resistance and high reliability performance in an adhesive joint, a degree of cure in excess of 75-90 % should be achieved [Chu10][Lu08]. This was only achieved with cure temperatures higher than 150 °C. With the lowest used cure temperature of 120 °C the curing degree was only 15 %. Even when the cure time was increased to 60 seconds the degree of cure only increased to 26 %. Consequently using a longer curing time was not a practical method to increase the degree of cure of the adhesive.

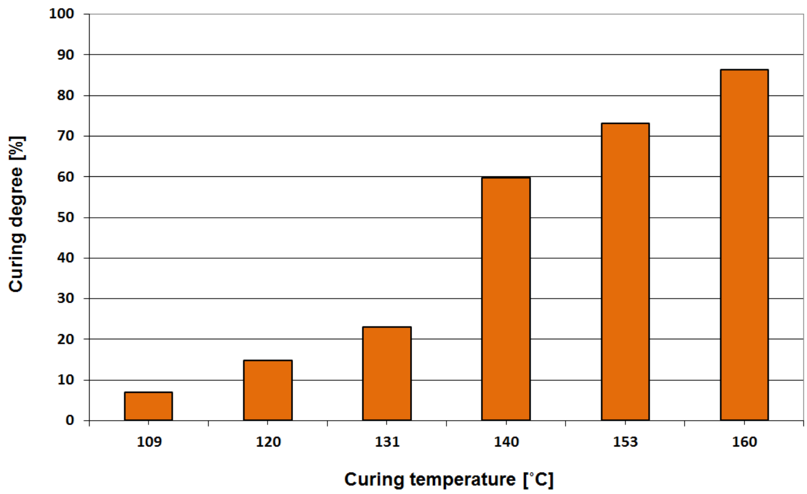

Figure 10: Adhesive degree of cure after 30-second curing at various curing temperatures.

Although the differences in the curing degree shown in Figure 10 were substantial depending on the cure temperature used, surprisingly small differences were observed in the peel test results. In other words, relatively good peel test results were observed in samples with low degrees of cure. This indicates that peel strength testing may not be a reliable method to determine if a proper curing degree has been achieved in the case of acrylic-based adhesives. A low degree of cure of an adhesive may cause reliability problems in use conditions because the mechanical strength will be less than that of a fully cured adhesive joint. Inadequate curing may cause the polymer matrix of an adhesive to relax and creep under mechanical stresses, which in turn may result in loss of contractive forces inside the adhesive joint and in increased contact resistance. Moreover, adhesive joints with a low degree of cure are more susceptible to swelling due to moisture absorption. [Cai09][Par06]

After peel testing the failure surfaces of the samples on the PCB were examined by SEM. Some variation in the failure modes were observed between samples with similar bonding parameters. However, clear differences were observed when batches of samples with differing bonding parameters were compared. In samples with the lowest curing degree the failure occurred mostly between the flex and the ACF, as the majority of the adhesive was observed to remain on the PCB side. However, the failure mode was observed to change in samples with higher cure temperatures and longer curing times. As mentioned, the cohesive and adhesion strengths of an adhesive joint increase with a higher degree of cure as the cross-linking of the polymer material increases. As a result of this, the amount of adhesive residue on the PCB side was observed to decrease. However, both cohesive and adhesion failures were observed in samples with the two lowest curing temperatures. In other words, although the overall amount of adhesive residue on the PCB side decreased, the failure mode, both on the contact pads and between them, was mixed. Only in samples with the highest curing degree had the failure of the assembly occurred almost completely between the ACF and the PCB as only a small amount of adhesive residue was observed on top of the contact pads of the PCB.

3.7 THERMAL TEST RESULTS

The effect of mechanical stresses caused by fluctuating temperature on the reliability of FOB attachments was studied with temperature cycling testing. The results are presented in this chapter. The changes in the reliability and resistance of the FOB assembly studied were first examined using a thermal cycling test with two soak times. In addition, the changes in the mechanical strength of the FOB attachment during temperature cycling aging were studied with a 90-degree peel strength test. Furthermore, in order to study the possibility of test time reduction the results obtained with the two soak times were compared.

3.7.1 Resistance measurements

The temperature cycling tests using the longer and shorter soak times were stopped after 10000 cycles. During this time no actual FOB joint failures were observed nor was any significant increase in the measured joint resistances. The average FOB joint resistances and their ±1 standard deviations calculated from the tested samples are shown in Figure 11. Because the FOB samples performed similarly in the real-time resistance measurement, no differences between the effects of the two temperature cycling test methods were observed. The drop in the resistance values observed at the start of the test was most likely caused by additional curing of the ICA used to connect the ground signal wire to the end of the PET flex. In addition, two slightly different ICAs were used with the 5 and 14-minute soak time samples, which explains the slight difference in the resistance values between them.

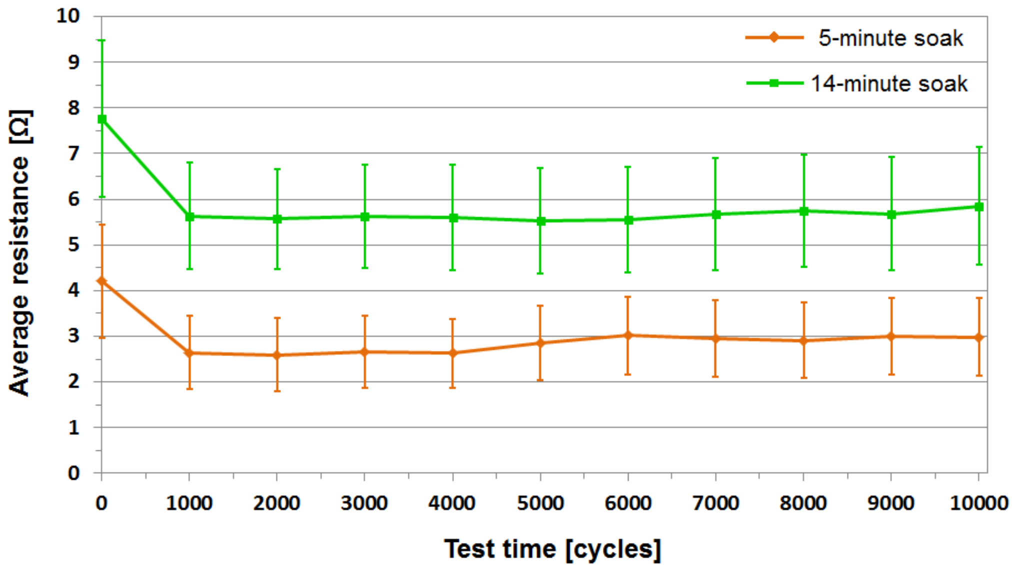

Figure 11: Average FOB resistance and standard deviation as a function of test time

3.7.2 Adhesion measurements

The effect of temperature cycling testing on the mechanical strength of the FOB attachment was studied by exposing batches of samples to both the test methods used. These samples were aged between 500 and 10000 cycles before subjecting them to the 90-degree peel strength test. The average peel strength values as a function of test cycles and their ±1 standard deviations calculated from the peel test results are shown in Figure 12. The mechanical strength of the FOB attachment studied was observed to drop significantly with both soak times used. Furthermore, with both test methods the most notable decrease in the peel test results occurred at the start of the test. However, according to the results the longer soak time resulted in a larger drop in the mechanical strength. Temperature cycling is known to induce thermo-mechanical stresses that may cause interfacial loss of adhesion and cracking of the adhesive [Ali05][Fri09][Kwo05]. Similar changes in the peel or shear strength results of ACF joints after 1000 cycles of temperature cycling have been reported in [Che06][Gao12]. However, in this study the observed decrease in the mechanical strength was more significant. Additionally, the test in this study was conducted markedly longer in order to study how the deterioration of the mechanical strength progresses under long-term exposure.

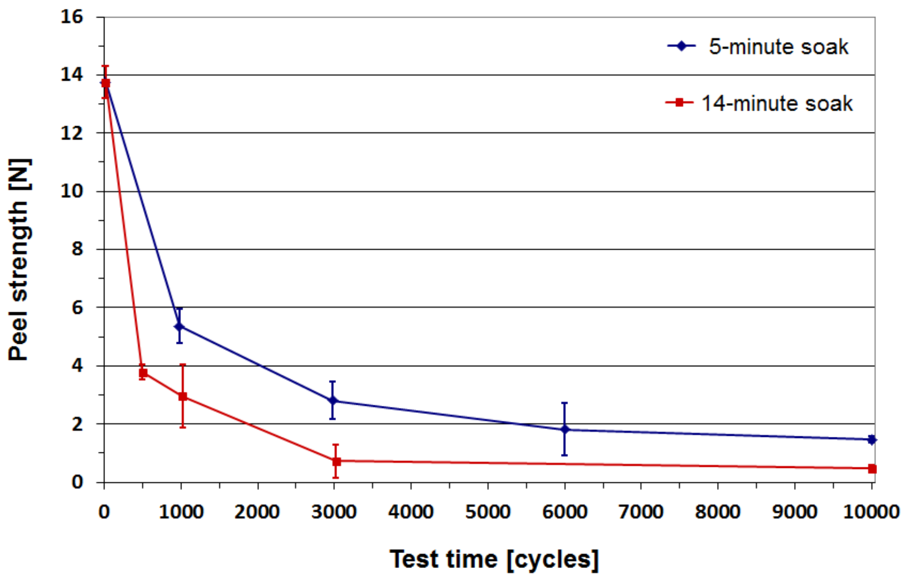

Figure 12: Average FOB peel strength and standard deviation as a function of test cycles

The fact that the two graphs shown in Figure 12 differed from each other indicated that the mechanical stresses induced during the temperature cycling were not solely responsible for the decrease in the peel strength results. Instead, the time spent at the high temperature extreme most likely also had an effect on the mechanical properties of the assembly. High temperatures, especially above the T_g of the adhesive, may cause further curing of the polymer matrix but it may also weaken the mechanical strength due to increased brittleness [Cha02][Law02]. In Figure 13 the aforementioned peel strength test results are shown as a function of test time. In this case the 5 and 14-minute soak time peel test results coincide with each other better than in Figure 12, above. According to the results obtained with the two soak times used, the time spent at the upper temperature limit seemed to have a greater effect on the mechanical strength of the FOB assembly studied than the number of temperature cycles. Consequently in this case the test time would not be affected by shortening the soak time at the temperature limits. However, additional testing with other soak times or a constant temperature test at 125 °C would be required to verify this result.

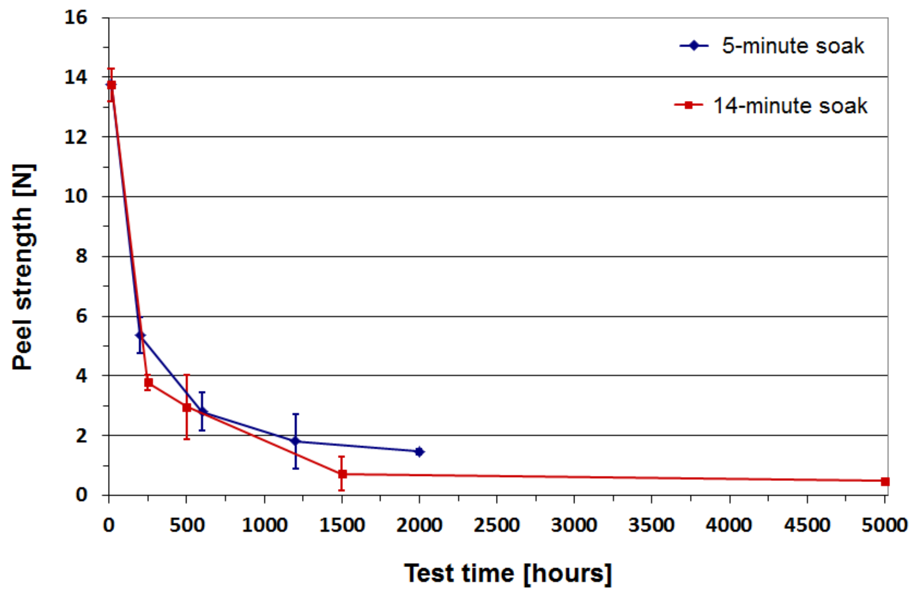

Figure 13: Average FOB peel strength and standard deviation as a function of test time

In addition to the experimental methods described in this chapter, predictive modelling could be utilized to obtain more detailed knowledge about the magnitude and location of stresses affecting the assembly. Such modelling could also be used prior to actual testing to improve the understanding of what kind of test structure and materials should be selected, what test method to use and how to implement it, and how to interpret the test results [Suh05][Suh09]. Predictive theoretical modelling can be divided into analytical and numerical models [Suh05][Suh09]. Analytical models are mathematical expressions that can be used to evaluate and calculate e.g. thermo-mechanically induced shear and peel stresses in an adhesive joint by using relative simple formulas [Suh86][Suh09]. Instead, numerical models are more complex and therefore require the use of computers. Today, finite element analysis is a commonly used method in the computational modelling of numerous engineering problems [Mot96][Roy01].

Despite the advantages of predictive modelling no analytical or numerical models were used in this work. The reason for this was to limit the scope of the thesis and the fact that the material properties of the two ACF materials used were unknown. Furthermore, the material properties of polymers may change during long-term testing which should be considered when predictive modelling is utilized. These methods, however, should be taken into consideration in further studies.

3.7.3. Failure analysis of peel tested samples

In order to study further the effects of temperature cycling, a failure analysis was conducted on the FOB attachments after peel testing. This was done by examining the failure surfaces of the peel tested samples using SEM and comparing test batches. In the case of samples without aging some variation in the failure modes was found but at the locations of the contact pads the failures were mainly observed to occur between the ACF and the PET flex. Between the contact pads the failure mainly occurred between the ACF and the solder resist of the PCB. Compared to untested samples, more variation was observed in the failure types and locations of aged samples. Due to this variation, no clear differences could be detected between samples with differing aging time or between the two soak times used. Although some signs of interfacial failures were observed, the detachment of the flex was mostly caused by cohesive failure of the ACF. Due to commercial reasons the material properties of the ACF used were undisclosed but it seems that during the high temperature soak time the adhesive may have cured further, which in turn may have caused it to become harder but also more brittle.

In addition to embrittlement, voids were found inside the adhesive in aged samples. Small voids were found in samples aged for only 500 cycles and the size of the voids was observed to increase as testing progressed. These voids were observed inside the adhesive film at the locations of the contact pads as well as between them. It seems that the smaller voids observed inside the adhesive joints may have been caused by evaporating solvents originating during additional curing of the ACF at the upper temperature extreme. In addition, out-gassing moisture or other substances from the solder resist or the PCB itself may have been the reason for the formation of larger voids observed between the contact pads [Lic05][Li06]. Void formation may weaken the mechanical strength of an adhesive attachment [Kim07]. According to the peel test results shown in Figures 12 and 13 the embrittlement and voiding of the adhesive already caused the main degradation of the mechanical strength of the FOB attachment during the first 500 or 1 000 temperature cycles.

3.8 HUMIDITY TEST RESULTS

In addition to thermal cycling the effect of humidity on the reliability of the FOB attachment was studied. The results are presented in this chapter. Two test methods with a constant elevated temperature and humidity settings were used in addition to a humidity cycling test and a high humidity temperature cycling test. During testing the FOB assembly samples were monitored by measuring their resistance in real-time. A 90-degree peel strength test was also used to examine the changes in the mechanical strength of the samples due to exposure to humidity.

3.8.1 Resistance measurements

The constant 65/90 test was continued for 5000 hours, during which no resistance values exceeding the failure criterion were observed. In fact, the measured resistance values remained unchanged throughout the test. The constant 85/85 test was concluded after 3500 hours, when 70 % of the monitored adhesive joints had shown a failure. The failures were observed to start after 2000 hours of testing. The 65/90 cycling test was discontinued after 4000 hours. By this time 40 % of the measured joints had exceeded the failure criterion. The 85/85 test with humidity cycling was stopped after 7056 hours or 882 cycles. During this time 18 % of the adhesive joints monitored had indicated a failure. Compared to the 85/85 test, where no failures were observed before 2000 test hours, the majority of the failures in the

85/85 cycling test were observed to occur early in testing. The cumulative failure percentages of the test methods used are shown in Figure 14.

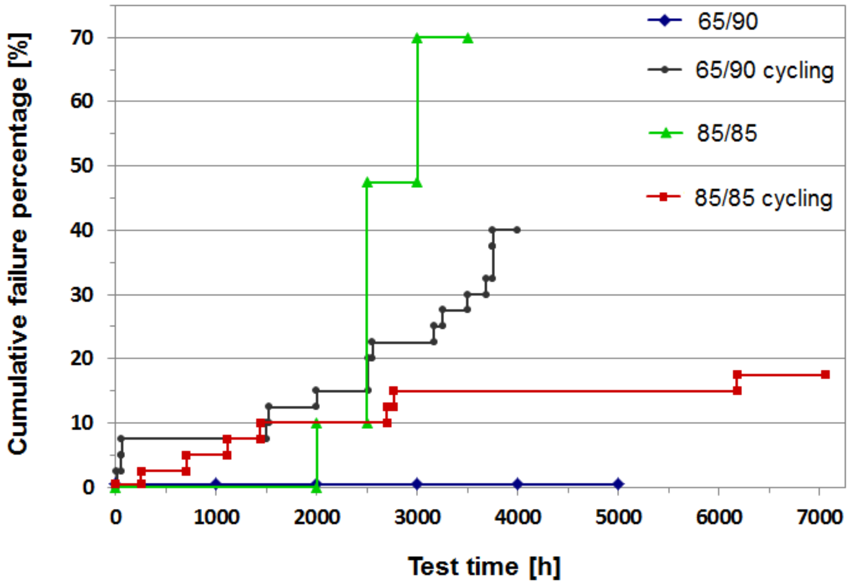

Figure 14: Failure percentages of the tested samples as a function of test time.

3.8.2. Failure analysis of monitored samples

65/90 and 65/90 cycling tests

After removal from the test the failure modes of the samples with resistance values exceeding the failure criterion were examined. Because no failures occurred during 65/90 testing no failure analysis was performed and the samples were subjected to peel testing. However, a failure analysis was done for the 65/90 cycling samples. For some of these test samples the failure analysis was complicated because conductivity problems were found between the PET flex and the ICA used to connect the ground signal wire to the FOB samples. In these cases it was difficult to ascertain if the elevated resistance values were caused by ACA joint failures, problems in the PET, or due to detachment of the ICA. However, in cases where the connection between the PET flex and the ICA was intact the failure analysis pointed to ACA joint failures.

In order to study the failures further, the ACA attachment of one FOB sample card was cross-sectioned while the four other sample cards were subjected to peel testing. The ACA joints indicating increased resistance values during testing were chosen and examined from the cross-sectioned sample with SEM. Delamination between the ACA and the contact pads as well as between the ACA and the conductor traces was noted (Figure 15). In addition, cracking of the adhesive was observed. Moisture is known to affect and degrade polymers due to plasticization and swelling but it may also induce voids, cracks, and interfacial delamination [Lin06][Liu07][Mub09].

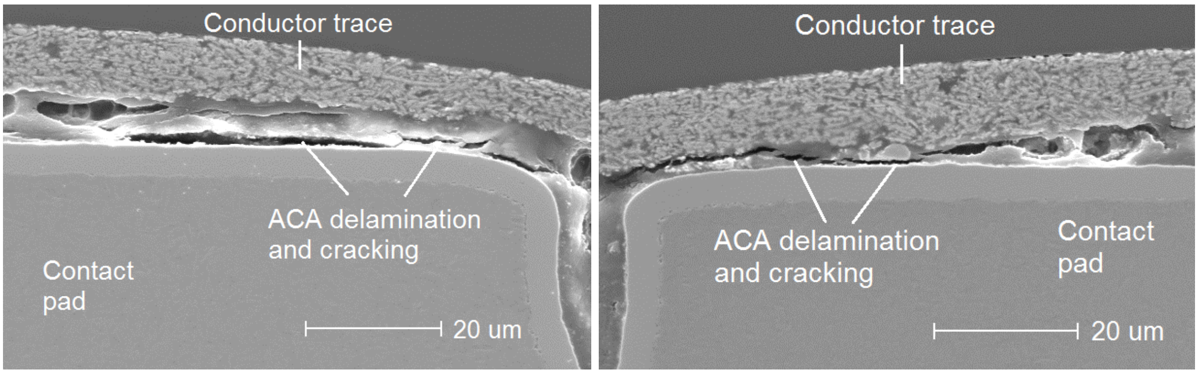

Figure 15: ACA joint failures in a sample aged 4 000 h in the 65/90 cycling test.

When the results from the 65/90 test and the 65/90 cycling test were compared, the condensation of moisture clearly had a significant effect on the reliability of the FOB assembly. Similar results have been reported in [Lai96] where temperature cycling under high humidity was observed to have a more marked effect on the reliability of ACA joints than constant humidity testing. However, humidity testing, where moisture condenses on the top of a product, is a very harsh testing method, and should therefore only be used if humidity condensation is a relevant stressor in actual use conditions. On the other hand, if condensation may occur during the use of a product, it is clearly a very critical factor. Condensation testing is not very widely used in electronics, but the results show that if condensation occurs testing in similar conditions may be a good method to bring out different failure mechanisms from those occurring in humid conditions without condensation.

85/85 and 85/85 cycling tests

The aging in the 85/85 test was observed to have caused changes in the material properties of the PET flex used as these had become harder and more brittle. Cracks were moreover observed in the flexes of all the tested samples, which, in some cases, had caused the conductors inside the flex to fail. A crack propagating through the conductor traces of a PET flex is shown in Figure 16. Cross-sections were also made from samples that had failed during testing based on the real-time resistance measurement. No signs of cracking, delamination or excessive voiding were found in the cross-sectioned samples with SEM analysis. Consequently the failures observed during testing were most likely caused by the cracking of the PET flex and the conductor traces within.

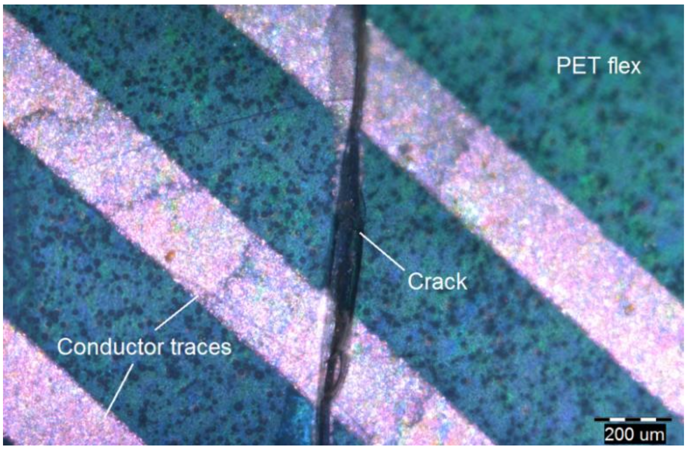

Figure 16: Cracked PET flex from an 85/85 aged sample.

The mechanism behind the embrittlement of the PET flex was most likely hydrolysis of the PET material. Hydrolysis is a chemical reaction where a compound breaks apart back to its constituents in the presence of water. In other words, the molecular structure of PET, like that of many other industrial polymers, contains ester groups that are susceptible to react with absorbed water at temperatures above their T_g [Bel95][Güç03][Lah13][Sam00]. In hydrolysis this reaction causes scission of the ester group and breaking of the polymer chain. This leads to smaller chain segments and lower mass molecules, which, in turn, results in a change in the material properties. Furthermore, temperatures exceeding the material's T_g enable realignment of these smaller chain segments causing a greater degree of crystallization and, therefore, brittleness [Bel95][Sam00]. Because the T_g of PET (70-78 °C [Cal07][Mat12]) is lower than the temperature used during the 85/85 test the flex was most likely exposed to hydrolysis. In addition, hydrolysis has been observed to reduce the ductility of PET during 85/85 testing [Lah13][Saa12].

Although the flexes in samples aged for 7056 hours in the 85/85 cycling test were too brittle for peel testing, no visual cracking of the flexes was observed. On the other hand, the time spent in 85/85 conditions during this test is only two hours per each eight-hour cycle, i.e. 1764 hours in total. This is less than the time elapsing before the first failures were observed in the 85/85 test. In addition, a longer time has been reported for PET to be visually embrittled due to hydrolysis at 85/85 conditions [Lah13]. Consequently the failures observed during the 85/85 cycling test were most likely attributable to other reasons than the cracking of the flex. As shown in Figure 14, the failure rate of the samples was observed to decrease rather than increase as the test progressed. Additionally, failures were only observed on two out of the five FOB assembly cards tested. This was thought to indicate that the failures were caused either by latent defects within the samples or by test setup malfunction. In order to study further the ACA joints, cross-sections were made from the tested samples. Only a few small adhesive cracks were found in the samples aged 7056 hours, as shown in Figure 17. Based on the SEM analysis these cracks were most likely not the reason for the elevated resistance values observed during testing. Other possible reasons for the failures could be the swelling and relaxation of the polymer matrix of the ACA. However, no such failures could be confirmed because they are difficult to detect with SEM.

Based on the failure analysis results from the 85/85 and the 85/85 cycling tests no clear failure modes other than the embrittlement of the PET flex were observed. Furthermore, the number of conductivity failures observed during the 85/85 cycling test was significantly small despite the long duration of the test. However, similar studies have shown that compared to constant temperature and humidity conditions, adhesive interconnections may be more susceptible to changes in temperature and humidity [Cae03][Saa12].

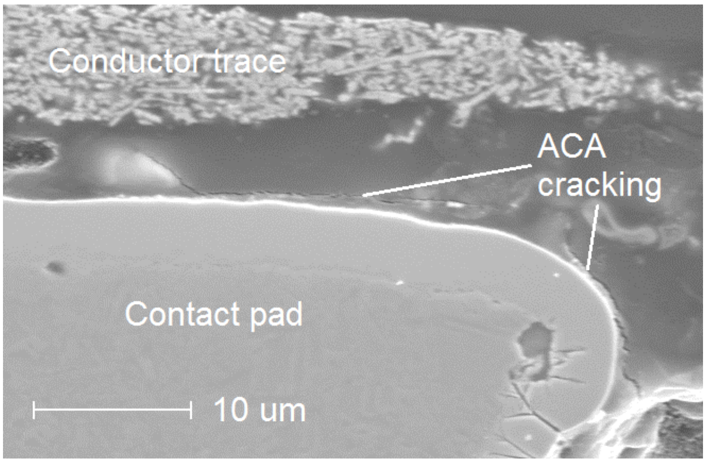

Figure 17: FOB ACA joint after 7 056 h of 85/85 cycling testing.

3.8.3 Adhesion measurements

The changes in the mechanical strength of the FOB assembly under various temperature and humidity conditions were studied by subjecting batches of samples to a peel strength test after they had been aged for a predefined period in the aforementioned tests. The average peel strength results calculated from the measurement data as well as their ±1 standard deviations are shown in Figure 18. As can be seen, differences in the test results from different test methods were observed. The 65/90 test had the smallest effect on the peel strength results. With this test the most significant drop in the mechanical strength occurred during the first 500 hours of testing and during the rest of the 5000-hour test the peel strength results were observed to remain almost unchanged. Although the peel strength of the FOB attachment decreased, no conductivity failures were observed during testing (Figure 14). In fact, according to the peel test results conducted on the thermal cycling aged samples (Figures 12 and 13) an even greater drop in the mechanical strength than in the 65/90 tested samples still does not compromise the electrical functionality of the adhesive attachment. Therefore, the PET FOB assembly tested may be extremely reliable even in harsh environments with humid conditions. However, such changes in peel strength may cause reliability concerns if the attachment is exposed to mechanical stresses in use. This should therefore already be taken into account in the design phase of a product. It also shows why it is important to be aware of the environmental factors that affect a product in service conditions.

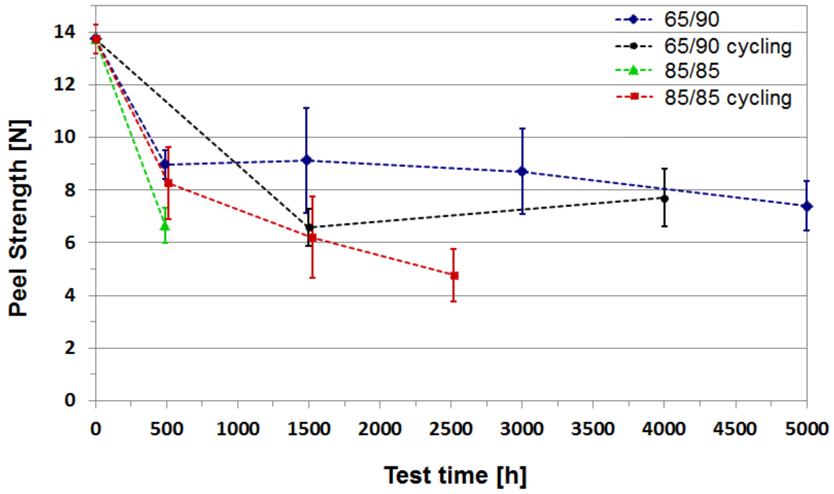

Figure 18: Average peel strength results as a function of test time.

With the 65/90 cycling test a higher drop in the peel strength results were observed after 1500 hours than in the 65/90 test samples. However, no additional drop was observed in the peel test results as the test progressed. After 4000 hours of aging the mechanical strength of the samples was found to be comparable to that of the 65/90 aged samples (Figure 18). Nevertheless, more data points would be required, especially at the start of the test, to enable more precise comparisons between the test methods.

The most notable decrease in the peel strength at the start of the test was observed in the 85/85 test. However, this test caused the PET flex to become brittle, which prevented the peel testing of the samples aged for 1500 and 3000 hours. Similarly, the embrittlement of the PET flex prevented the peel testing of the samples aged for 7056 hours in the 85/85 humidity cycling test. Nevertheless, the peel test results obtained with the 85/85 cycling test showed that the mechanical strength of the FOB assembly decreased faster than in the 65/90 test. This was most likely caused by the differences in the moisture diffusion rates, the amount of absorbed moisture inside the adhesive, and the stresses caused by moisture expansion as they are all dependent on the ambient temperature and relative humidity [Bon06][Fan09].

Similar decreases in the mechanical strength of epoxy-based adhesive joints have been reported where the rapid decrease in adhesive joint shear strength at the start of testing is observed to even out as testing progresses [Bro99][Gao12][Saa11b]. Furthermore, the joint strength was observed to decrease with time towards a constant value which depended on the used temperature and relative humidity values [Bro99].

3.8.4 Failure analysis of peel tested samples

SEM analysis was used to study the failure surfaces of the peel tested samples. As mentioned earlier, adhesive interfacial failures were observed at the locations of the contact pads in samples without aging. Although some adhesion failures were observed between the ACF and the contact pads, in most cases the failure had occurred at the interface between the ACF and the flex. With the samples aged in the 65/90 test a larger amount of adhesive residue was first observed, after 500 hours of testing, on the solder resist of the PCB. The failure mode at the location of the contact pads had remained the same as with samples without aging. On the other hand, after 1500 hours the amount of adhesive residue on top of the contact pads had increased substantially. The failure mode had again changed after 3000 hours of testing as a large amount of the conductor trace material from the flex was observed on the PCB side. The amount of this conductor trace material on the PCB was found to have further increased in the 5000-hour aged samples. This phenomenon was not observed in the thermal cycling aged samples. The changes in the failure mode due to hygrothermal aging are illustrated in Figure 19. On basis of the findings it seems that the aging in 65/90 conditions first weakened the adhesion between the ACF and the PET flex. Then, as the test time increased, the adhesion between the conductor trace material and the PET flex degraded and became the limiting factor for the mechanical strength of the FOB assembly. This, however, did not have a marked effect on the peel strength test results as shown in Figure 18.

The failure modes of the 65/90 cycling samples resembled those of the 65/90 samples. However, the amount of conductor trace material found on the PCB side was observed to differ between the test methods. With the 65/90 cycling test the amount of conductor trace material found on top of the contact pads remained relatively low and constant even after 4000 hours of testing. This may have been caused by the delamination and cracking of the adhesive as shown in Figure 15. That is, although the interfacial strength between the conductor traces and the PET flex most likely decreased as in the 65/90 test, the failure of the assembly during the peel test propagated through the ACF’s cracks and interfacial delaminations.

Similar changes in the fracture surfaces were seen in the samples aged in the 85/85 test and the 85/85 cycling test, although the embrittlement of the PET flex prevented the failure analysis of some of the samples. Especially in the case of the 85/85 cycling test, the failure of the assembly was observed to change from ACF - flex interfacial failure to the detachment of the conductors from the flex between 1512 and 2520 test hours. However, the difference was that in the 65/90 test the almost complete detachment of the conductor traces occurred after 5000 h whereas the same occurred in half the time in the 85/85 cycling test.

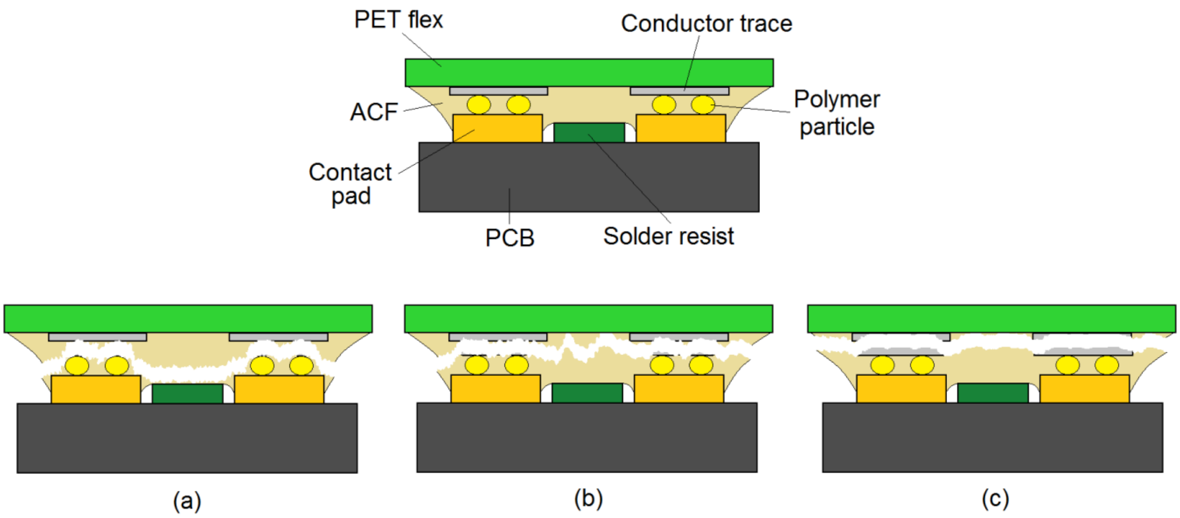

Figure 19: Illustration of the changes in the failure locations observed due to 65/90 aging. Failure locations (a) without aging, (b) after 1500 hours, and (c) after 5000 hours.

4 SYSTEM LEVEL RELIABILITY TESTING: FREQUENCY CONVERTER

The reliability analysis of products at system level is often very challenging because the number of possible failure mechanisms and modes may be markedly higher than in component level testing. That is to say, not only is failure analysis more complicated but also if a product fails during testing due to a number of different and unrelated reasons, it may be difficult to make conclusions about the overall reliability of the design. This may also be further complicated by the fact that the sample size is often small due to cost or availability issues. However, in some cases product level testing may be the only feasible method to study the overall reliability of a device and the possible interaction effects between components and sub-assemblies as well as to identify the possible weakest links in the design.

4.1 FREQUENCY CONVERTER

Currently, due to their widespread use electric motors are responsible for more than half of the power consumed by industry [Fer11][Sai12]. In most cases these applications still utilize fixed-speed electric motors with a constant output [Kim12][Fer11]. A frequency converter (FC) or a variable speed drive is a device that controls the speed, direction of rotation and torque of motor systems in order to improve process control while saving energy and improving efficiency [Bro05]. Additionally, FCs can be used to decrease the thermal and mechanical stresses affecting motors and thereby increasing overall system reliability [Sai12][Kim12]. Consequently FCs have become a cost effective solution for a variety of industrial applications with high reliability and low maintenance requirements that use alternating current (AC) motors [Bar03].

4.1.1 Basic operating principle

The main components of an FC operated AC motor drive are shown in Figure 20. The FC is connected between a three-phase power supply and an AC motor, which in turn is connected to the actual load. The FC itself comprises a rectifier section, a DC bus, and an inverter section with its associated control circuitry. The rectifier section is usually composed of six power diodes in a full-bridge configuration, which converts the three-phase AC from the power supply to DC. Electrolytic capacitors of the DC bus then smooth the rectifier output and provide a fixed DC voltage. The inverter section is used to convert the DC back to a three-phase AC with variable voltage and frequency. The inverter usually consists of six insulated gate bipolar transistors (IGBT) with free-wheeling diodes [Sai12]. A separate control circuitry using pulse width modulation (PWM) is commonly used to operate the IGBTs [Bar03][Sai12]. The auxiliary power for the control circuitry itself is obtained from the DC bus voltage through a switched mode power supply, which is basically a DC-DC converter [Bar03].

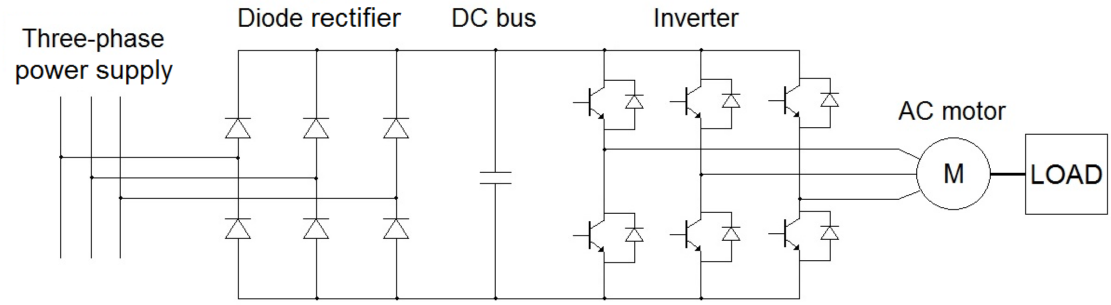

Figure 20: Main components of a frequency converter.

4.1.2 Applications and service environments

FCs are commonly nowadays used in various applications ranging from pumps, fans, compressors and conveyors to differing processing and machining applications such as paper mills and rolling mills. [Sai12][Bar03][Fer11] The power rating of FCs also ranges significantly from sub-kilowatt up to megawatt range [Bar03]. Because of their wide range of application and the fact that FCs are used all over the world the service environments that FCs are subjected to also vary considerably. This may complicate product design and the analysis of field failures because the environmental stresses affecting the reliability of the devices are not always known.

4.2 TEST SAMPLES

The system level testing performed in this work was done using two FC models. In Publication IV an older generation model was used in order to study the effects of the environmental stress tests used on the observed failure modes and to compare them to field failure data. In Publication V a newer generation model was subjected to test conditions similar to those used with the older generation device in order to compare their reliability performance.

The power rating of the three-phase FC used in Publication IV was 750 W. It was composed of a single PCB and an aluminium casing. The input voltage and frequency range of the device were 380-480 V_{AC} and 50-60 Hz respectively. The corresponding output voltages and frequencies were 0-480 V_{AC} and 0-120 Hz. The insulated gate bipolar transistors (IGBTs) and the rectifier diodes were located in a separate power module between the PCB and the aluminium casing, which also functioned as a heat sink.

The device tested in Publication V was likewise a 750 W three-phase FC with comparable input/output voltage and frequency ranges. It was, however, composed of two PCBs inside a casing made out of acrylonitrile-butadiene-styrene and polycarbonate (ABS/PC). The base plate of the device was polycarbonate with glass fibre reinforcement (PC/GF). The two PCBs were connected to each other with a signal cable and located on top of each other inside the casing. A separate power module housing the rectifying stage and the IGBTs was mounted on the bottom PCB. The power module had an aluminium heat sink with a 50 mm fan attached.

4.3 TEST EVALUATION METHODS

Test data evaluation methods similar to those used in interconnect level reliability testing were also used at system level. However, the more complex the device to be tested is, the more difficult the test setup and the interpretation of test data typically become. The selection of the characteristic signals required for monitoring the performance of samples during testing should be made carefully in light of comprehensive knowledge of the device. A real-time monitoring method is again preferable in order to obtain information about the first signs of abnormal performance and how it then progresses to a complete failure. To enable this, the device being tested needs to be powered on during testing.

4.3.1 Motor drive current

The operability of the two FC models was monitored during testing by measuring the current going through the sample devices. This motor drive current was measured inductively from one of the three phases of the voltage input. During testing the frequency converters were used to drive 80 Hz AC motors cyclically. The drive command signal was given by a timer and each drive cycle comprised 15-second “on” and 45-second “off” periods. A metal weight plate was attached to each AC motor to act as a nominal load.

A National Instruments LabView program was used to control and monitor the tested frequency converters. The control program measured and logged the motor drive current from each device tested in addition to monitoring the drive command signal. If no current was observed at the time when the timer gave the drive command, the program would shut the particular sample off by opening its supply voltage contactor. This was done in order to prevent further damage to the sample. The operating principle of the test set up is shown in Figure 21.

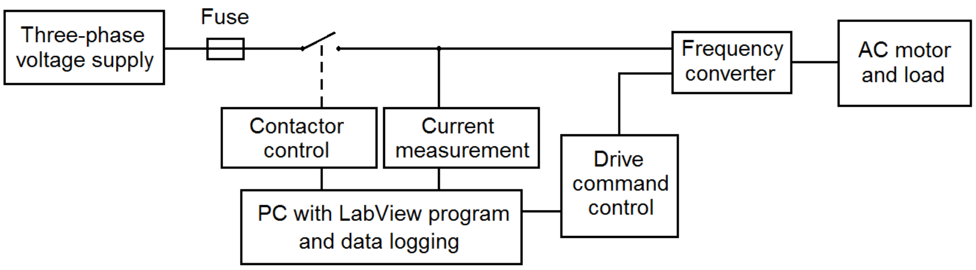

Figure 21: Block diagram of the test setup used with frequency converters.

4.4 RELIABILITY TESTS

The system level reliability of two FC models was studied using differing environmental stresses both separately and simultaneously. The object was to study how the usage of concurrent stresses may be used to shorten test time when compared to single stress tests. In addition, the failure modes observed were studied and compared to the field failure data. The applicability of using the same test method to compare the reliability of two device generation models with differing constructions was likewise examined. Although the service conditions of the FC models tested may include a number of diverse stress factors, this work concentrates on the effects of elevated temperature and humidity, increased supply voltage and voltage interruptions.

4.4.1 Overvoltage and voltage interruptions

In Publications IV and V the old and new generation FCs were subjected to both input overvoltage and voltage interruptions. Based on prior knowledge about the service conditions of the FCs voltage fluctuations were considered a likely stress factor. The motor drive cycle was the same as before, but the three-phase input voltage was increased with an AC generator from the nominal 400 V_{AC} to 500 or to 520 V_{AC}, which was the highest operable voltage rating of the old generation device. The frequency of the voltage was kept the same, at 50 Hz.

The voltage interruptions were performed at the start of each drive cycle. The control program was used to switch off the supply voltage contactors three seconds into each drive cycle. The duration of the voltage interruption was 0.15 seconds. This value was obtained by studying the older generation device. With longer interruption times the device was not able to recover from the power outage.

4.4.2 Temperature and humidity test

A constant temperature and humidity test based on JEDEC's JESD22-A101C standard was used in Publications IV and V [JED09a]. The temperature and relative humidity values in this test were 85 °C and 85 % respectively, and it was performed in 500-hour test runs. This test was conducted by placing only the frequency converters inside a test chamber. Other test equipment including the AC motors remained in room conditions.

4.5 TEST RESULTS

The reliability of two FC models was studied at system level. Different environmental stresses were used separately and in combination in order to activate the same failure mechanisms that affect the service life of the products in use conditions. In addition, the aim was to study the effect of concurrent stresses and to develop a test method that would minimize testing time through acceleration of failures. The results are presented in this chapter. The testing was first started with the old generation device as failure data was available from actual service conditions for this device. This knowledge was then used to compare test results obtained from different test methods. Similar test methods were subsequently used to examine the reliability of the new generation device that still lacked field failure data from use conditions.

4.5.1 Old generation device

Three test methods were used with the old generation FC. The first test was a constant 85/85 test with a nominal supply voltage of 400 V_{AC}. In the second test method the sample devices were operated at room temperature with an overvoltage of 520 V_{AC} and voltage interruptions. The third test method was a combination of the first two, i.e. an 85/85 test with overvoltage and voltage interruptions. The cumulative failure percentages of the aforementioned test methods used are shown in Figure 22.

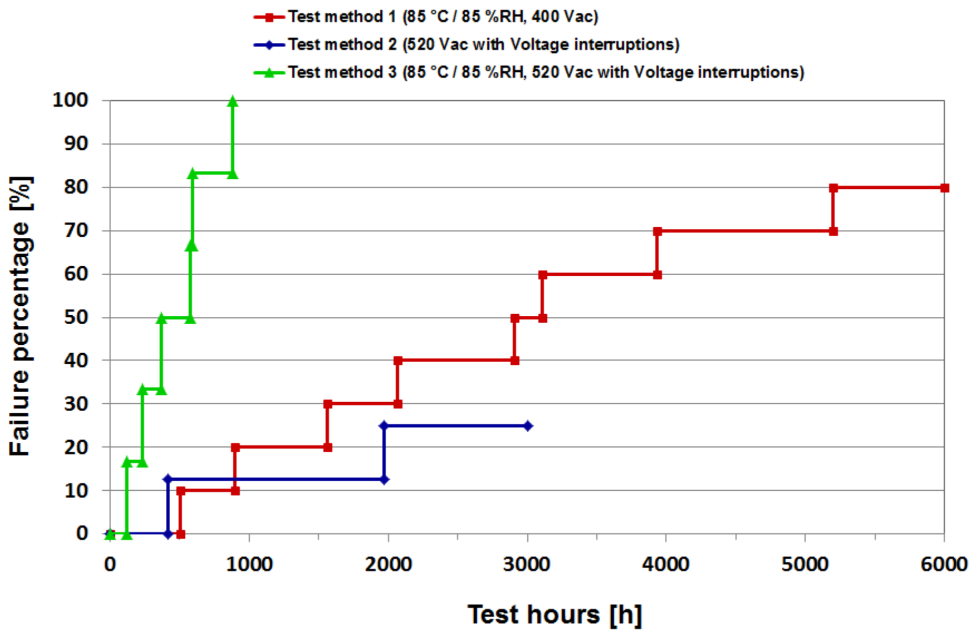

Figure 22: Failure percentages of the test methods used with the old generation device as a function of test time.

Test setup 1

The first test was stopped after 6000 hours, during which eight out of the ten samples were noted to have failed. During the test many of the devices had dropped offline a number of times, but if the particular sample was able to operate normally after a reset the testing was continued. Instead, if a sample had tripped its circuit breaker or if it was not able to function normally it was deemed to have failed. The failure times and observed failure modes of the samples are shown in Table 4. The first sample that failed after 504 h was removed from the test as it indicated a short circuit error with its signal LEDs. Five of the tested samples were observed to drive the AC motors without the drive command, i.e. a small but continuous current was measured from the samples during the "off" period of a drive cycle. Instead, one sample ceased to drive the AC motor for no apparent reason. The last device to fail suffered from a shorting of an auxiliary power supply field-effect transistor (FET). The subsequent failure current had also burned the gate and source resistors of the FET (Figure 23).

Table 4: 85/85 test results with nominal supply voltage.

Failure time (h):	Failure mode:
504 h	Bond wire heel cracking
895 h	Unable to switch off after "on" cycle
1 563 h	Unable to switch off after "on" cycle
2 064 h	Unable to switch off after "on" cycle
2 910 h	Unable to drive the motor
3 110 h	Unable to switch off after "on" cycle
3 931 h	Unable to switch off after "on" cycle
5 196 h	Power FET and gate/source resistors failure
-	-
-	-

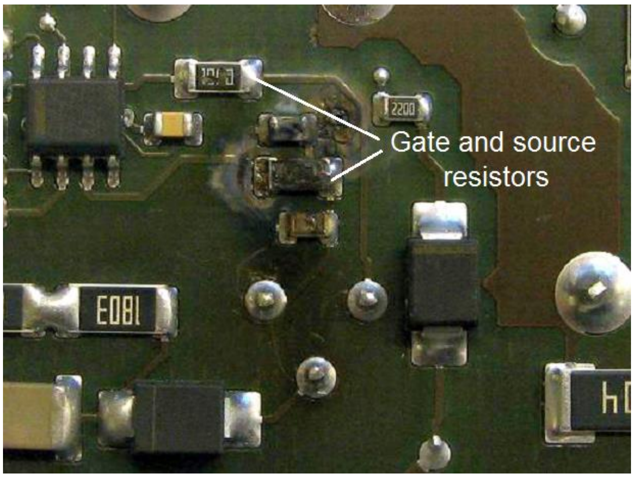

Figure 23: Burned gate and source resistors due to FET shorting.

A failure analysis was performed on the failed samples in order to study further the observed failures modes and the possible mechanisms that led to the failure. In addition, the relevance of the failures compared to the field failure data was also examined. A broken aluminium bond wire was found inside the IGBT module of the sample that failed first. However, this failure was most likely caused by a manufacturing flaw because such a failure mode is usually only observed after a long-term exposure to thermal cycling [Cia02]. Furthermore, this was the only occurrence of this failure mode. In the case of the five sample devices that were observed to continuously drive the AC motors no apparent reasons for the failures could be established. However, in light of the field failure data this kind of failure mode had not been observed in service conditions. It was therefore concluded that, although the failure mechanisms behind the observed failures could also be present in use conditions, other environmental stresses may have a more profound effect on the reliability of the device. Instead, the power FET short circuit failure mode was considered to be applicable to service conditions. During normal operation switching transistors may heat up significantly, which in turn results in thermo-mechanical stresses inside the component [Cia02][Lut11][Zha09].

Test setup 2

The second test method performed at room temperature with overvoltage and voltage interruptions was discontinued after 3000 h. During this time only two samples had failed. The failure times and failure modes are shown in Table 5. The reason why only the two samples failed was their older IGBT module version. The rest of the samples in this test as well as the samples used in the two other test methods had a newer power module with redesigned layout. A failed IGBT is shown in Figure 24. The IGBTs of power converter applications are known to fail in use conditions due to varying system, environmental and wear-out related causes [Cia02][Tri99][Per08][Per11]. However, this result clearly shows that due to excessively long testing time overvoltage and voltage interruptions alone are not an applicable test method in the case of this particular device type.

Table 5: Overvoltage (520 V_{AC}) with voltage interruptions test results.

Failure time: (h)	**Failure mode:**
420*	IGBT short circuit
1 970*	IGBT short circuit
-	-
-	-
-	-
-	-
-	-
-	-

* Differing (older) IGBT module version.

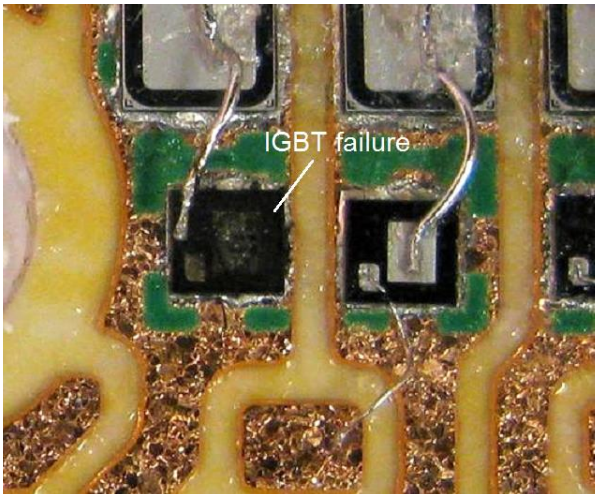

Figure 24: IGBT short circuit failure.

Test setup 3

The third test method combined the stresses used in the first two tests, i.e. elevated temperature and humidity conditions (85/85) and overvoltage and voltage interruptions. The results are shown in Table 6. All the samples failed before 900 h of testing. In the case of three samples the failure of the device was caused by a dielectric breakdown that occurred inside the PCB (Table 6). A power FET short circuit failure was observed in two samples. Additionally, one sample failed because of an IGBT short circuit. The concurrent usage of the environmental stresses clearly reduced the overall test time when compared to the first two test methods.

Table 6: 85/85 test results with overvoltage (520 V_{AC}) and voltage interruptions.

Failure time: (h)	Failure mode:
123	PCB dielectric breakdown
233	Power FET and gate/source resistors failure
369	IGBT short circuit
575	PCB dielectric breakdown / Discharge resistors failure
590	PCB dielectric breakdown
881	Power FET and gate/source resistors failure

The dielectric breakdown in samples that failed after 123 h and 590 h was observed to have occurred between the two topmost layers of the PCB at the location of a DC bus and one of the three input phases. The dielectric failure had occurred under a DC bus electrolytic capacitor, which was removed to facilitate failure analysis (Figure 25). A similar dielectric breakdown was also found in a third sample near the same place but this time inside the PCB. The dielectric failure had also expanded the bottom surface of the PCB causing a detachment of two discharge resistors.

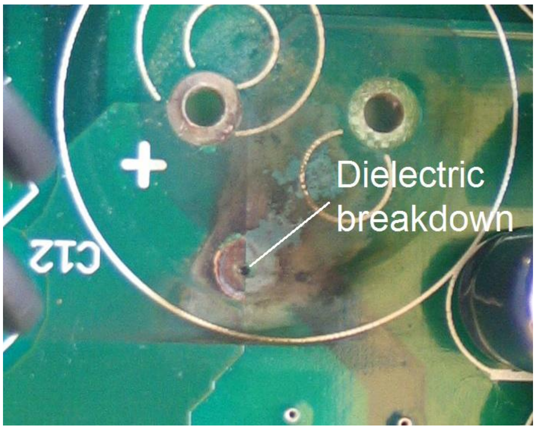

Figure 25: PCB dielectric breakdown.

As such failures did not occur during the first two test setups, the combination of increased operating voltage with voltage interruptions and elevated temperature and humidity clearly had a significant effect on the dielectric strength of the device. Although the dielectric strength of an FR-4 is considerably higher than the voltages used in this test [Coo01] these failures may have been caused by localized electric fields or due to material properties such as defects, voids and contaminants. In addition, the test temperature and local heating may have had a significant effect. With polymers the number of charge carriers generated inside the material increases rapidly due to heating, which in turn results in decreased electrical resistance. An electric field may then increase the current density inside the material through Joule heating, which may further increase the temperature locally. In the worst case this situation may lead to thermal runaway and to the breakdown of the dielectric material [Dis92]. However, this failure mode was not applicable to the field failure data from service conditions. Therefore, as the combined effect of the 85/85 test and the usage of overvoltage were as significant as shown by the results, a more moderate overvoltage value should be used in order to reduce the risk of a dielectric breakdown. In other words, by lowering the probability of dielectric failures the occurrence of other failure modes may be studied further.

In addition to the dielectric breakdowns failure modes applicable to actual field failures were also observed during the simultaneous stress testing. The power FETs of two test setup 3 samples had suffered a short circuit failure similarly to a sample in test setup 1. However, contrary to the failure time of 5196 h of the sample from test setup 1, the aforementioned devices of test setup 3 failed after 233 h and 881 h. In other words, by using concurrent stresses the respective failure times were reduced by 96 % and 83 %. An IGBT failure was likewise observed in another sample in test setup 3 after 369 h of testing. Nevertheless, when the two differing tests are compared, especially in the case of simultaneous stresses, the test results should be interpreted with caution. Different environmental stresses may activate differing failure mechanisms that may still cause similar failure modes. Moreover, the combined effects of various failure mechanisms and their impact on failure modes are still largely unknown [Car98][Eck09][Qi09][Wit12].

To obtain in-depth knowledge about the effects of the stresses used on the failure modes and mechanisms of the sample device a notably larger sample size should be used. Additional studies would also be needed to examine the effects of the test temperature and humidity individually on the failures observed. The use of overvoltage and voltage interruptions should likewise be studied separately. However, this would require a significant amount of testing time and resources as using only one stress may not suffice to produce failures in a reasonable amount of time in the case of high reliability devices such as the FC tested.

4.5.2 New generation device

The new generation frequency converter samples were subjected to three test methods based on the results obtained with the old generation device. Namely, testing in room conditions was not used, as it was shown to be an ineffective method. Furthermore, the stress that was varied between test methods was the level of overvoltage used. The first test method was a constant 85/85 test with nominal supply voltage of 400 V_{AC} but with the 0.15 s voltage interruptions. The second test method was the same as the first one, but with an elevated operating voltage of 500 V_{AC}. In the third test method a supply voltage value of 520 V_{AC} was used in addition to the 85/85 test and voltage interruptions. This was the same test as that used in test setup 3 with the older generation device. The cumulative failure percentages of these test methods are shown in Figure 26.

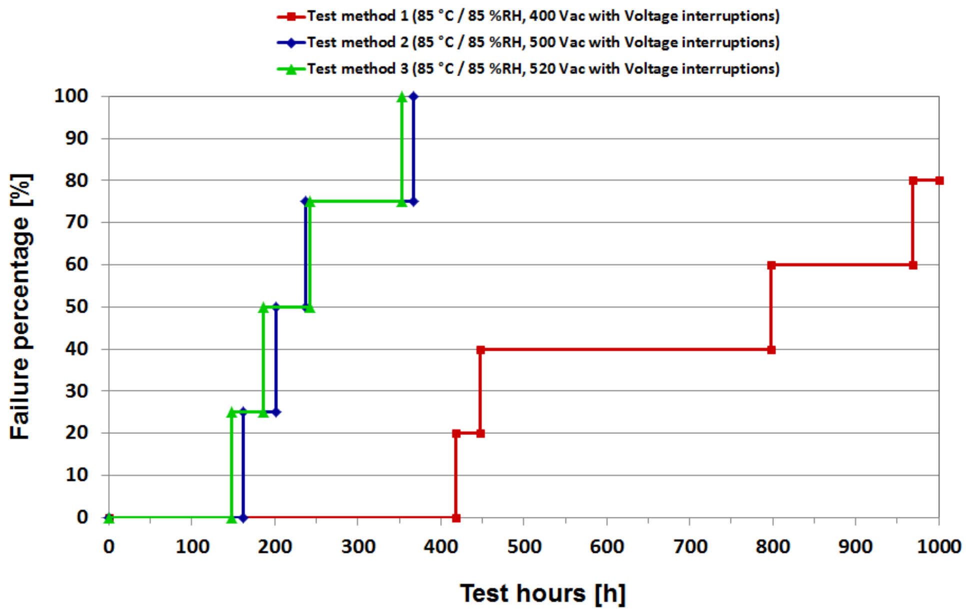

Figure 26: Failure percentages of the test methods used with the new generation device as a function of test time.

Test setup 1

The first test method with the new generation device was stopped after 1000 h during which four out of the five samples tested had failed. The failure times and modes are shown in Table 7. During the test some of the samples had suffered from occasional offline drops, but as no signs of abnormal operation were observed the test was continued after a reset. Two of the FCs tested were observed to fail suddenly during the "off" period of a drive cycle, and in both cases the devices could no longer be switched on. After removal from the test these samples were still inoperable. On the other hand, one sample failed as it was observed to drive the AC motor constantly. A reset was attempted a number of times but the device did not recover. The same failure mode was also observed in room conditions. The last sample to fail switched off during an "off" period of a normal drive cycle. After a reset the sample indicated a "parameter fault" error and remained inoperable. However, after the test the device was again observed to operate normally.

Table 7: 85/85 test results with nominal voltage (400 V_{AC}) and voltage interruptions.

Failure time: (h)	Failure mode:
418	Does not switch on
448	Drives the AC motor constantly
798	Does not switch on
969	"Parameter fault" error
-	**-**

When the samples were removed from the test for a failure analysis the ABS/PC casings were observed to have deformed and shrunk. The plastic had also become so brittle that it broke when the samples were disassembled. Because the polymer casing was an essential structural part of the device, this prevented the reassembly and further testing of the devices. Only the PC/GF bottom plates had remained intact. The failure analysis did not reveal further information on the failures observed.

Because the T_g of the ABS/PC material was above the test temperature no significant changes in the material properties were expected. In order to study this finding further the changes in comparable ABS/PC material during 85/85 aging was examined with DSC analysis. According to the results the T_g of the material changed from the original value of 102 °C to 93 °C and 82 °C after 500 h and 1000 h of testing respectively. This was most likely caused by plasticization of the ABS/PC material due to absorbed moisture [Hag11]. In addition, physical aging of the casing material may also have occurred. During this structural recovery process the molecular chains of a glassy polymer move and rearrange themselves to recover from a non-equilibrium state caused by rapid cooling after moulding of the material [Hut95]. This causes the material to shrink. The structural relaxation is also accelerated when the temperature is increased towards the T_g of the material. Furthermore, the degree of crystallinity of the casing material may have increased, which would explain the brittle behaviour after testing. This same deterioration of the casing material was observed in all subsequent tests. Although frequency converters are often used in harsh environments, such changes in the casing material properties are unlikely in service conditions. Consequently, using elevated temperature and humidity may complicate the interpretation of test results and their comparison to actual use conditions. However, the casing was an integral part of this particular device and could therefore not be removed prior to testing.

According to the failure analysis, the deformation and shrinking of the ABS/PC casing may have had an effect on the failure of the samples. For example, the changes in the casing may have caused mechanical pressure on the components and the connectors inside the device. In addition, the air circulation inside the device may have been affected as the casing shrank. Nevertheless, the verification of the effects of the ABS/PC shrinkage was difficult because the reassembly of the deformed and broken casing was not possible.

Test setup 2

All the samples subjected to the second test method were observed to fail during the first 500-hour test run. As shown in Table 8, the tested devices failed in a notably shorter period of time compared to that of the previous test. Moreover, the failure modes differed significantly from those found with the first test method. The first sample already failed after 162 h, when its circuit breaker was tripped by a current spike during AC motor deceleration. The second failure occurred at the start of a drive cycle just before the voltage interrupt. The circuit breaker did not trip but the sample was unable to restart. The last two samples also failed at the start of a drive cycle before the voltage interrupt. The last sample to fail had its circuit breaker tripped by a current spike at the time of the offline drop. In the case of the third failure a similar current spike occurred when a reset was attempted.

Table 8: 85/85 test results with overvoltage (500 V_{AC}) and voltage interruptions.

Failure time: (h)	Failure mode:
162	PCB dielectric breakdown, Power-FET and IGBT short
202	PCB dielectric breakdown
237	Power-FET and IGBT module diode short
367	IGBT module diode short

Failure analysis of the tested samples revealed failure modes similar to those found with the older generation device. A switching transistor failure of the device's internal power supply was observed in two samples. In both cases the power FET had short-circuited between the gate and source terminals, which had also burned the source resistors and the gate resistor in one of the samples. In addition, a rectifying diode failure was found inside the power modules of two samples. This is a typical failure type for switch-mode power supplies [Zha09]. Another typical failure mode, IGBT short circuit, was also observed.

The dielectric breakdowns observed during testing of the old generation device model were also found in two samples. In these samples the failure had occurred between one of the output phases and a chip capacitor that belonged to a snubber circuit (Figure 27). This circuit was used to protect the power FET from high voltage switching transients.

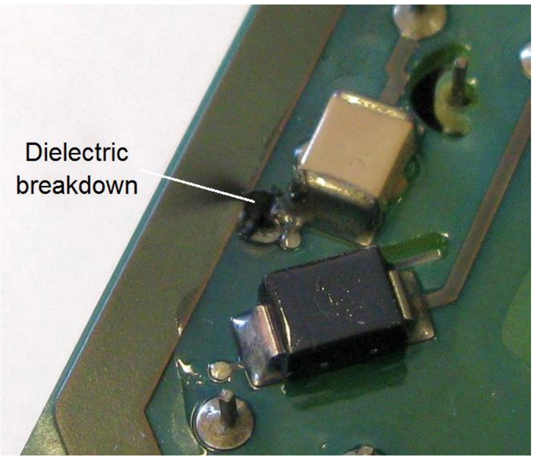

Figure 27: PCB dielectric breakdown.

Test setup 3

The highest overvoltage value was used in the third test method, namely the same test which was used on the older generation device. The results are shown in Table 9. The failure times of these devices were similar to those of the samples in test setup 2, but the failure modes differed markedly. The first device that failed malfunctioned at the end of a drive cycle and could not be turned on despite reset attempts. The testing of the second failed device was stopped because the AC motor drive current was measured to be discontinuous and resetting of the device did not help. The third sample to fail suffered from recurring offline drops during which the device indicated an overheat failure. After a reset the sample would operate normally for a short while before the same thing reoccurred. The last sample ceased to operate abruptly for no apparent reason. Because it did not respond to resets the testing was stopped.

Table 9: 85/85 test results with overvoltage (520 V_{AC}) and voltage interruptions.

Failure time: (h)	Failure mode:
148	PCB dielectric breakdown
186	Discontinuous AC motor current
242	Overheat error due to obstructed cooling fan rotation
353	Does not switch on

During failure analysis a dielectric breakdown was found in one sample near the same snubber circuit as with the samples in test setup 2. This time, however, the dielectric failure had occurred between the same output phase and an adjacent via. The second and fourth samples to fail were not tested at room temperature before removal from the test in order to avoid causing further damage. No obvious reasons for their abnormal operation were found in a visual inspection and measurements made with a multimeter. It is, however, plausible that these failure modes may only be replicated in test conditions. In the case of the sample with overheat failures the signal cable connecting the two PCBs was found to have obstructed the rotation of the cooling fan. This in turn had caused the device to overheat. The reason for this failure was most likely deformation of the plastic casing, which should not occur in normal use. No additional failures were found in the device.

4.6 COMPARISON OF DEVICES TESTED AND TEST METHODS

According to the tests conducted and the field service data, the older generation device had a considerably high reliability, which may cause problems in test method development. In other words, significantly high stress levels are required in order to accelerate failures sufficiently and to minimize test time, but at the same time the risk of inducing failure mechanisms and modes irrelevant to the service conditions may increase [Suh02][Nel04]. In the case of the older generation FC applying simultaneous stresses was observed to be an applicable method for test time reduction, but understanding the combined effects of the stresses applied would necessitate extensive further testing.

Moreover, with the new generation device the concurrent use of environmental stresses resulted in a marked reduction in test time when compared to a single stress test. The failure types were also comparable to those observed in service conditions. However, the direct application of the same concurrent stress test method for both FC generations examined proved difficult. This was mainly due to differing constructions and material selection. In other words, the elevated temperature and humidity test condition affected the material properties of the plastic casing of the new generation device, which complicated the interpretation of the test results. The effects of this on the test results were inconclusive because the casing was an integral part of the device and therefore could not be removed. To avoid this, the temperature and humidity settings used should have been lowered, but this would have necessitated additional testing with both generation device types to enable comparison. The test results from both device types also showed that the use of overvoltage and voltage interruptions as accelerating factors warrants further study. According to the results the selection of a practical overvoltage value should be carefully considered in order to avoid unrealistic PCB dielectric breakdowns in conditions of elevated temperature and humidity. Research conducted with a comparable device showed that supply voltage interruptions performed during either acceleration or deceleration under 85/85 conditions had a clear effect on the failure modes and failure times of an FC [Pip12]. That is, with voltage interruptions the failure mode was observed to change from IGBT failures to power FET failures. To conclude, this research demonstrated the importance of valid field failure data from actual use conditions without which the development and improvement of such testing methods would not have been possible. Additionally, depending on the use environment, other stresses affecting the lifetime of a product, such as vibration, mechanical impacts, corrosive gases or salt, could also be considered [Eck09][Kii09].

The monitoring of the FCs during testing should also be developed further as the measurement of the motor drive current from the input was not found to be a practical method to stop the devices before a catastrophic failure. Furthermore, the logged measurement data was not observed to be of use in the prediction of failures. The measurement of additional information from the tested devices, e.g. DC bus voltage, power FET temperature, or three-phase output current, could improve the monitoring method. However, due to the high voltages found inside the device, caution should be exercised during the measurements.

Although the interaction effects of various simultaneous environmental stresses and their failure mechanisms are still not completely understood, it is important to take them into account during reliability analysis. If the stress factors in a given service condition are known, the study of their combined effect might yield important information on the robustness of the product and also help in the analysis of field failures. However, experience and engineering judgement are needed because it is impossible to take account of every environmental factor. This requires knowledge about the product to be tested including its design, materials and operating principles, as well as knowledge of the service conditions, the environmental stresses and their severity.

Even though there are several challenges, the interest in using combined environmental stresses in reliability testing has increased due to the possibility of test time reduction and the better characterization of actual use conditions. However, the modelling of the interaction effects of failure mechanisms and the extrapolation of test results to use conditions still remain challenging and require further research [Mat11a][Qi08][Wit12]. One main focus area of such research has been the application of simultaneous vibration and thermal cycling in the reliability testing and lifetime prediction of solder joints [Eck09][Mat11b][Qi09][Wit12]. The two main approaches in these studies for combining the vibration and thermal cycling induced damage have been the linear superposition method and the incremental damage superposition method. The former approach is similar to the Palmgren-Miner rule, where the damage rates caused by the two stresses are calculated individually and then added together without considering the possible interaction effects [Bar91]. Instead, the incremental damage superposition approach takes into account the interaction effect between the changing temperature and the damage induced by vibration. That is, the temperature induced stresses in the solder joints and the changes in temperature dependent coefficients, such as the fatigue and the ductility coefficients are taken into consideration when calculating the vibration induced damage [Qi08][Upa98]. However, in contrast to the relatively simple implementation of the linear superposition method, the utilization of the incremental damage superposition approach can be substantially more complex, incorporating finite element analysis [Eck09].

When the two approaches for combining vibrational and thermal cycling damage have been compared to laboratory test results, the linear superposition method seems to significantly overestimate the lifetimes of the solder joints. On the other hand, the incremental damage superposition approach has yielded better estimates although its precision seems to depend on which of the two stresses is predominant. [Eck09][Qi08][Wit12]

As mentioned, the incremental damage superposition approach has been reported to give good results for solder interconnections. However, solder interconnections are relatively simple structures and therefore can be modelled and analysed even with such complex models. When a whole product is considered its modelling becomes considerably more complicated. Consequently, modelling may not be possible or its results may be decidedly inaccurate. Therefore experimental testing such as that conducted in this work is essential to gain a better understanding of the joint effects of the various environmental conditions.

5 CONCLUSIONS AND FINAL REMARKS

Electronic products need to be sufficiently robust to perform their function in specific conditions for specified amounts of time even though they are subjected to a number of different stresses during manufacturing, assembly, transportation, storage, maintenance and use. One possibility to try to ensure adequate performance of products is to perform reliability tests that can be used to study how, why and when products fail under controlled conditions. Because the planned lifetime of an electronic product may be decidedly long compared to development cycles, acceleration of test time is often required. This is commonly achieved by exposing products to higher environmental stresses or to a greater number of use cycles than they would normally be subjected to in their conditions of use. However, the challenge is to ensure that the failure mechanisms being accelerated during testing are the same ones which are responsible for actual failures in the field. Furthermore, if stresses are increased too much, new failure mechanisms may be activated that are not normally observed and may not even be possible in the use conditions of a product.

In this work accelerated reliability testing methods were studied for products with high reliability requirements and long service lives. The applicability of different testing methods for test time acceleration was examined and their effect on the observed failure modes and mechanisms was studied. The challenges and limitations of the test methods used were moreover discussed. Commonly used standard tests were taken as the starting point of the research and the effects of changes and modifications to the test parameters were studied. The research was conducted at both interconnection level and at device level. The interconnection level reliability testing focused on the anisotropically conductive adhesive (ACA) flex-on-board (FOB) attachments of a display device which was used as a user interface to a frequency converter. The reliability of the ACA FOB structures has been studied earlier for use in consumer electronics but knowledge of their long-term performance in industrial applications with long lifetimes has been lacking. In addition, the usability of a cost effective polyethylene terephthalate (PET) flex with ACA attachment technology was studied. The test methods applied included thermal cycling and elevated temperature and humidity tests.

It was observed that according to real-time resistance measurements the ACA attached PET flex assembly may even be applicable to applications with a long service life which are subjected to harsh environmental conditions. However, the mechanical strength of the FOB attachment was measured to decrease significantly during environmental testing. This should be taken into consideration during product design. According to the thermal cycling tests performed it seemed that, with this assembly, the amount of time spent at the high temperature extreme may have had a greater impact on the mechanical strength of the FOB attachment than the number of cycles performed. However, further studies on the properties of the ACA and the effects of longer soak times on the peel strength are required. On basis of the hygrothermal tests performed, accelerating test time by using harsher conditions was not applicable, because the higher test temperatures exceeded the T_g of PET which eventually resulted in hydrolysis and embrittlement of the flex. The hydrolysis of PET is very unlikely to occur under the actual storage and use conditions of the device and therefore such a failure mechanism was not meaningful for this product. The only clear indications of ACA joint cracking were observed with moisture condensation testing. However, this kind of stress may not be applicable to all use environments and therefore its use needs to be carefully considered.

The curing process of ACA interconnections affects significantly the properties and reliability of the attachments. Therefore it is essential to understand the effects of process parameters. In this work the effect of varying bonding temperature and curing time in the case of an acrylic-based ACA was studied by measuring the mechanical strength of a FOB test structure with several different combinations. The results showed that although adequate peel strength was obtained with all used curing temperatures the ACA's degree of cure was significantly low with low curing temperatures. However, a longer curing time did not improve the peel test results or the curing degree. Only with the highest curing temperature a satisfactory degree of cure was obtained and an increase in the peel test results was noticed when curing time was increased.

In addition to the interconnection level testing, the system level reliability of two frequency converter (FC) models was examined in this work. The effects of differing environmental stresses were examined both separately and concurrently in order to develop a test method to induce similar failures as observed in service conditions. An important aim was to look for testing methods that would cause failures with a minimum amount of testing time. The field failure data available for the older generation device model and the engineering knowledge of the manufacturer were used as a reference to which the observed failures during testing were compared. Similar test methods were then applied to the newer device model and the failure modes and overall reliability were compared between devices. The used stresses applied included a constant temperature and humidity test, increased supply voltage and voltage interruptions.

The results for the older generation FC clearly showed the accelerating effect of using stresses simultaneously compared to using them separately. Because of the robust design of the device, the use of a single stress was observed to be challenging. In order to be able to induce failures in a practical amount of time, an extremely high stress level would have been required. On the other hand, when multiple stresses are used concurrently the severity of individual stresses may be reduced. Although failure modes comparable to field failure data were observed during testing, the combined effect of differing stresses on the actual failure mechanisms remained unclear. In order to facilitate failure analysis more information should be measured from the devices during testing. This would most likely also improve the prediction of upcoming malfunctions before catastrophic failures occur. However, determining the signals to be measured is typically very challenging, requiring in-depth knowledge of the device. The applicability of using the same test method for both new and old generation devices also proved challenging. Although similar failure modes were observed in both devices, the differences in materials, components and layouts complicated the analysis of the stress factor effects.

The results show how challenging the application of concurrent stress testing can be, especially in the case of a complex device. The main disadvantage is that the interpretation of the test results is complicated because of the interaction effects of the failure mechanisms. Further studies would be needed for a more profound understanding of the combined effects of the different stresses. Additionally, due to the complexity of such testing, the results obtained may be highly application specific, which inhibits their use on dissimilar products. However, regardless of the complexity of using simultaneous stresses as a lifetime estimation method, it was observed to be a practical method to study the weaknesses in a product. In order to learn more about concurrent stress testing a larger sample size should be used and additional tests with lower stress severities should be conducted. Because a number of different failure modes were observed while testing, the statistical reliability analysis could also be improved by using right censored data. That is, each failure type would be analysed individually so that samples failing due to other failure mechanisms would be included in the analysis but as suspensions. However, such an approach would require a relatively large number of tested samples to obtain sufficient numbers of each failure type.

Table 10 lists the non-standardized test methods used in this study. The 65/90 cycling and the 85/85 cycling tests were used in the interconnection level reliability testing of the FOB assembly. The 85/85 test with nominal supply voltage and the overvoltage and voltage interruptions as well as their combination were, in turn, used in the system level testing of the FCs.

Table 10: A summary of the novel test methods used in the study.

Test method:	Test device:	Test duration:	Failures : (%)
65/90 cycling	FOB	4000 h (1600 cycles)	40
85/85 cycling	FOB	7056 h (882 cycles)	18
85/85 with nominal supply voltage	FC	6000 h	80
Overvoltage and voltage interruptions	FC	3000 h	25
85/85 with overvoltage and voltage interruptions	FC	1000 h	100

Compared to the standard tests with constant temperature and humidity, both the interconnection level cycling tests showed interesting results. The 65/90 cycling test with moisture condensation was in particular observed to have a significant effect on the ACA attachments tested. However, as mentioned earlier, its use as an accelerated testing method should be carefully considered. If condensation is expected during the service life of a product, moisture condensation testing is an interesting and most likely very useful alternative, also applied on system level. On the other hand, if no condensation occurs under the use conditions, it may cause incorrect failure mechanisms. The 85/85 cycling test, which did not incorporate moisture condensation, was developed because a number of ACA attachment failures had previously been observed to occur during the start or the end of constant 85/85 testing when humidity was either increased or decreased. The 85/85 cycling test was observed to cause some failures in the FOB assembly tested, but considering the overall test duration, it did not accelerate failures sufficiently in the test structure studied. Therefore, its overall effectiveness on adhesive attachments should be studied further. Overall, the FOB assembly studied was observed to be very resilient to conductivity failures, which caused excessively long testing times. However, according to the peel strength results, changes in the mechanical strength of adhesive attachments should instead be monitored more closely and at short intervals during the start of testing.

The standard 85/85 test used also during the system level testing is a very common test in electronics. However, it is an extreme test environment for most commercial electronics. On the other hand, in the case of high reliability devices such as the FCs tested in this work, the test method proved to be insufficient by itself due to the testing time required (Table 10). Additionally, the overvoltage and voltage interruptions used were found to be inadequate test conditions for test time reduction. Nevertheless, the standard 85/85 test should still be considered a baseline test method in the case of system level testing and monitoring of high reliability devices. As mentioned earlier, a significant test time reduction may be achieved by combining the two previous test methods. However, the greater the need to reduce the test time is, the greater are the risks of inducing overstress failures rather than wear-out failures.

The following paragraphs summarise the main results of the publications.

Publication I, "The Effect of Bonding Temperature and Curing Time on Peel Strength of Anisotropically Conductive Film Flex-On-Board Samples", studied the effect of bonding parameters on the ACA joints of a FOB test structure. Differing curing temperatures and times were used and their effect on the mechanical strength of the FOB attachment was studied with a 90-degree peel strength test. In addition, the curing degree of the ACA was examined with differential scanning calorimetry. Although an adequate mechanical strength was obtained with all the curing temperatures used, this was clearly observed to increase with the bonding temperature. Longer curing time mainly increased the standard deviation of the peel test results and improved the mechanical strength only with the highest temperature used. Low curing temperatures resulted in a markedly low curing degree even with longer curing times and a sufficient degree of cure was achieved only with the highest curing temperature. The failure location in the peel test was also observed to change as the curing degree changed.

Publication II, "Reliability Analysis of an ACA Attached Flex-On-Board Assembly for Industrial Application", concentrated on the applicability and long-term reliability of an ACA FOB attachment used in an LCD user interface device. A standard -40/+125 ºC thermal cycling test with two soak times was used in order to study the possibility of test time reduction. In addition to real-time resistance measurement, the changes in the mechanical strength of the FOB attachment were studied with a 90-degree peel strength test. The FOB attachment proved to be very reliable as no ACA joint failures were observed during testing.

However, the peel test results decreased significantly, especially at the start of the temperature cycling tests. When the results from the two soak times used were compared, the time spent at the upper temperature extreme seemed to have a greater impact on the mechanical strength than the number of thermal cycles. In addition to void formation in the adhesive, a change in the failure mode of peel tested samples was observed from interfacial delamination to cohesive failure due to temperature cycling.

Publication III, "Hygrothermal Aging of an ACA Attached PET Flex-on-Board Assembly", examined the long-term reliability of an ACA FOB attachment used in an LCD user interface device in humid conditions. The test methods included constant temperature and humidity tests as well as humidity cycling and moisture condensation tests. Real-time resistance monitoring was used during testing and a 90-degree peel strength test was used to study changes in the mechanical strength of the FOB attachment. Significantly long testing times were required in order to observe failures. However, the test methods with temperatures exceeding the glass transition temperature (T_g) of the polyethylene terephthalate flex caused it eventually to become brittle due to hydrolysis. This complicated the analysis of the results and restricted the use of peel testing. No significant decrease in the peel strength results was observed with the other test methods. In addition, conductivity failures due to ACA delamination and cracking were only observed in the humidity condensation test.

Publication IV, "System-Level Reliability Testing a Frequency Converter with Simultaneous Stresses", studied using concurrent environmental stresses as a device level reliability testing method in the case of a frequency converter. The effects of elevated temperature and humidity and of overvoltage and voltage interruptions on the failure modes and testing time were examined separately and simultaneously and compared to actual failure data from service conditions. The results showed that only by combining the stressors used could a significant reduction in testing time be achieved and failure modes comparable to use conditions were observed. However, different concurrent stresses may cause complex interactions between failure mechanisms that complicate the interpretation of test results. Therefore, in-depth knowledge of the tested device and the service environment is required.

Publication V, "Reliability Analysis of Two Frequency Converter Generations Using System-Level Stress Testing", examined the feasibility of using the same simultaneous stress testing method to compare the reliability of an old and a new frequency converter model. The test methods were similar to those presented in Publication IV. The combined stresses to which the new generation device was subjected included elevated temperature and humidity, voltage interruptions and differing supply voltage values. The environmental test results were then compared to those of the old generation device and its actual field failure data. Similar failure modes were observed but the interpretation of the test results proved challenging due, for example, to differing designs, material properties and components.

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ISBN 978-952-15-3359-4
ISSN 1459-2045