Chapter 1
Introduction

The foundation of this book is that mechanical and functional properties are defined by microstructure, atomic bonding structure, and chemical composition [1]. This is approached by following the path of microstructure evolution and identifying the microstructure interaction with the external environmental factors. Before getting into these factors and their influence and effects, we will consider the interaction between the electronic device and our daily life. With the world covered with more electronic devices and the higher dependency on the signals into and out of these devices, identifying the elements that react to these external factors is crucial. In this chapter, we will briefly look into the overall landscape we are living in and the variety of design expectations of electrical components and devices in various end-use conditions. We will identify external factors and their relationship with the term "reliability."

Electronic Device in Our Lives

Electronic devices are used virtually everywhere. Since Ewald Georg von Kleist and Pieter van Musschenbroek invented the Leyden jar in 1745, an electrical storage device, considered as one of the first uses of electricity for an electric circuit [2], and after William Watson discharged the Leyden jar through a circuit in 1747 [3], electronic devices have been in our everyday lives ever since. Of course it needed several revolutionary milestones like the invention of the transistor, the personal computer, and the Internet, which ultimately connects revolutionary milestones to enable us to reach the entire world today. But it is clear that we are more attached to electronic devices than at any other time in history.

During this revolutionary transformation, electronic devices not only evolved in its internal function, but they have evolved in their ability to connect with other devices. First, the power grid dominated, by connecting houses and factories, and then the telephone transferred a very small amount of information compared to

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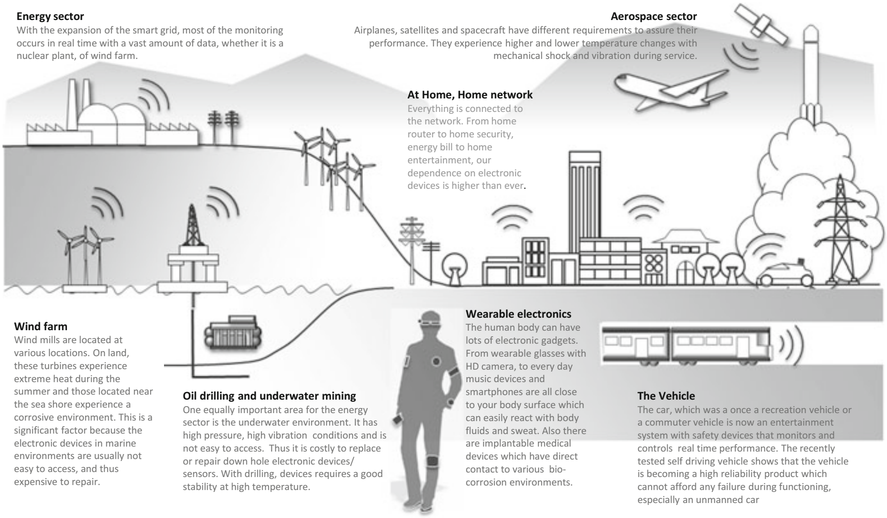
today's data capacity through copper lines. Today, it is the still evolving Ethernet cable that connects the world with high-speed information and streaming data input from virtually everywhere, from a personal electronic device to the massive traffic of information into and out of a "cloud" or in another term, an era of "Internet of everything (IoE)."

With this connectivity, data transport, and control over various electronic devices, the functionality of a device is becoming more versatile, and the end-use conditions are getting much broader. Areas once not reached by electricity now have massive current flowing through electric devices, serving as critical controllers, which are ultimately responsible for the safety of their users. Figure 1.1 depicts the overall relationships we live within with representative devices used in our daily life, directly or indirectly, from a simple handheld device to transportation control systems and energy monitoring devices.

A good example of the deep penetration of electronic components and devices into our daily life can be found in the automobile sector. Compared to a decade ago, we have many more electronic devices in our cars. There are basic on/off switches, brake control systems, electronically controlled shock absorbers, engine and transmission control systems, GPS and entertainment systems connected to the Internet, and so on. With the increasing variety of devices, the role of these electronics becomes crucial to assure the safety of the car and its occupants, while being more efficient, more fun, and more informed. Automobiles have become some of the most advanced electronic products on the market today. With the introduction of in-car instrumentation, navigation capabilities, safety features, and so-called infotainment technologies, the vehicle electronic systems become increasingly complex. As a result, the challenge to assure the reliable performance of automotive electronics



Energy sector
With the expansion of the smart grid, most of the monitoring occurs in real time with a vast amount of data, whether it is a nuclear plant, of wind farm.

Aerospace sector
Airplanes, satellites and spacecraft have different requirements to assure their performance. They experience higher and lower temperature changes with mechanical shock and vibration during service.

At Home, Home network
Everything is connected to the network. From home router to home security, energy bill to home entertainment, our dependence on electronic devices is higher than ever.

Wind farm
Wind mills are located at various locations. On land, these turbines experience extreme heat during the summer and those located near the sea shore experience a corrosive environment. This is a significant factor because the electronic devices in marine environments are usually not easy to access, and thus expensive to repair.

Oil drilling and underwater mining
One equally important area for the energy sector is the underwater environment. It has high pressure, high vibration conditions and is not easy to access. Thus it is costly to replace or repair down hole electronic devices/sensors. With drilling, devices requires a good stability at high temperature.

Wearable electronics
The human body can have lots of electronic gadgets. From wearable glasses with HD camera, to every day music devices and smartphones are all close to your body surface which can easily react with body fluids and sweat. Also there are implantable medical devices which have direct contact to various bio-corrosion environments.

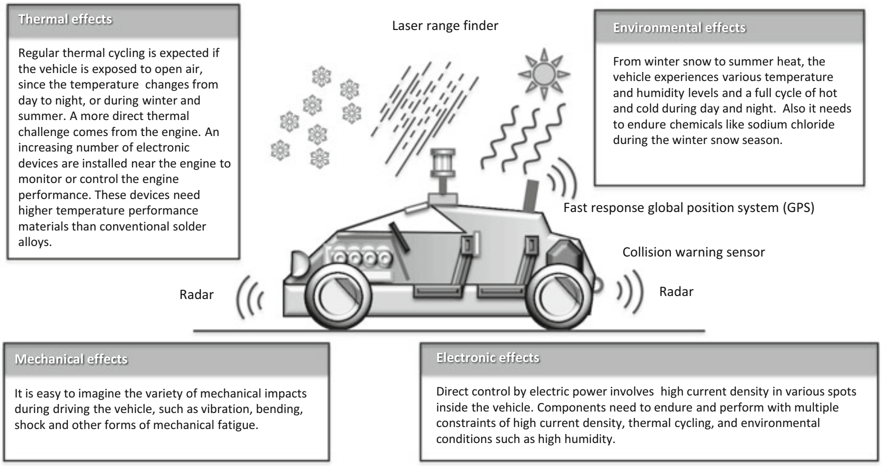
The Vehicle
The car, which was a once a recreation vehicle or a commuter vehicle is now an entertainment system with safety devices that monitors and controls real time performance. The recently tested self driving vehicle shows that the vehicle is becoming a high reliability product which cannot afford any failure during functioning, especially an unmanned car

Fig. 1.1 Overall landscape of electronic use conditions from sea level to underground, vehicles, our bodies, and home is greater than ever. Self-driving vehicles are in development, which ultimately need a very high level of reliability to assure that the vehicle and the adjacent vehicles on the road will be safe. A shift from a vehicle loaded with noncritical and independent electronic systems to a highly integrated and reliable system is becoming a reality.

A similar high-reliability level is required in other sectors such as Internet routers in the telecommunication industry. A vast amount of information and data need to be delivered with a high bandwidth and without interruption. The aerospace sector needs assured reliability both for airplanes and ground systems, because repairing a satellite is too expensive to be a viable option. The same is true for ocean wind turbines. Offshore wind farms are regions where the most wind exists, which are often a place on earth where extreme environmental and temperature fluctuations exist, from very cold static conditions with no wind to hot daytime temperatures with high wind. These wind turbines experience high vibration and corrosion environment, which are all challenges to the long-term reliability of devices. But one of the most severe thermal and mechanical shock and vibration environments for electronic systems is the oil drilling sector. Underground drilling sensors, like the satellites in space, cannot allow a reliability issue since it is too expensive to repair [4].

Given the demands and opportunities, how can we confidently say that an electronic device or system is acceptable and safe to use for an important safety-related end-use condition and be qualified as reliable? To make that assessment, the service conditions the device experiences need to be identified, define the important factors and boundary conditions that affect the stability of the device, and find the degradation mechanism(s). Using this approach, the expected lifetime of the device can be estimated.

Revisiting the automobile example in Fig. 1.2, a regular thermal cycling is expected if the vehicle is exposed to open air, with day and night thermal cycling, or during winter and summer, but a more direct thermal challenge comes from the engine itself.



Thermal effects

Regular thermal cycling is expected if the vehicle is exposed to open air, since the temperature changes from day to night, or during winter and summer. A more direct thermal challenge comes from the engine. An increasing number of electronic devices are installed near the engine to monitor or control the engine performance. These devices need higher temperature performance materials than conventional solder alloys.

Environmental effects

From winter snow to summer heat, the vehicle experiences various temperature and humidity levels and a full cycle of hot and cold during day and night. Also it needs to endure chemicals like sodium chloride during the winter snow season.

Mechanical effects

It is easy to imagine the variety of mechanical impacts during driving the vehicle, such as vibration, bending, shock and other forms of mechanical fatigue.

Electronic effects

Direct control by electric power involves high current density in various spots inside the vehicle. Components need to endure and perform with multiple constraints of high current density, thermal cycling, and environmental conditions such as high humidity.

Fig. 1.2 An example, in this case a vehicle, what external factors can influence and impact the stability and functionality of the electronic device during service

An increasing number of electronic devices are installed near the engine to monitor or control the engine performance. These devices need higher temperature materials, where conventional solder materials are inadequate. From winter snow to summer heat, the vehicle also experiences various humidity levels and needs to tolerate chemicals like sodium chloride during the winter snow season. It is easy to imagine the variety of mechanical impacts like vibration, bending, shock, and other mechanical fatigue processes during driving the vehicle. The electric or hybrid vehicles, which are directly controlled by electric power, also have high-density currents in various locations inside the vehicle circuitry. An increasing number of components perform with high current density combined with severe environmental conditions. Thus, there are thermal, mechanical, electrical, and environmental challenges which need to be overcome in an electronic loaded car to be reliable for a long enough time. It is important to learn from the drastically failed components, to know the mechanisms responsible for electronic system degradation and failure, and it is often challenging to find a solution that will mitigate one mechanism, without facilitating another mechanism that can cause failures.

Expected Lifetime

The expected lifetime of a component varies with the character of the device and its purpose or end-use condition. Table 1.1 shows the general life expectancy based on several practical categories [5]. For example, the expected lifetime for a personal computer or a smart phone is not the same as a commercial aircraft. As shown in the table, the expected lifetime of a commercial aircraft is 10 years with a tolerable failure rate of 0.001 %, which is a very high expectation compared to a 2-year life expectancy with 1.0 % failure rate for consumer electronics. Then how can we insure that our products will meet these expected lifetimes for each electronic product category? What do we need to consider to make this product function safely? The answer can be found in the next section “Reliability.”

The Difference Between Quality and Reliability

As we have a variety of devices, we have also a variety of different reliability expectancies. Reliability can be defined in various ways, but a representative definition is the quality or state of being reliable or the extent to which an experiment, test, or measuring procedure yields the same results on repeated trials. There are also some expanded definitions, such as the idea that an item is fit for a purpose with respect to time; the capacity of a designed, produced, or maintained item to perform as required over time or the probability of an item to perform a required function under stated conditions for a specified period of time; or the durability of an object [6].

Table 1.1 Product categories and worst-case use environments for surface mounted electronics [5]

	Worst-case use environment				
Product category (Typical application)	$T_{\min}$ °C/°F	$T_{\max}$ °C/°F	ΔT °C/°F	Typical years of service	Approx. accept. failure risk, %
Consumer	0/32	60/140	35/63	1–3	1
Computers and peripherals	0/32	60/140	20/36	5	0.1
Telecomm	–40/–40	85/185	35/63	7–20	0.01
Commercial aircraft	–55/–67	95/203	20/36	20	0.001
Industrial and automotive-passenger compartment	–55/–67	95/203	20/36	10–15	0.1
Military (ground and shipboard)	–55/–67	95/203	40/72 and 60/108	10–20	0.1
Space	–55/–67	95/203	3/5.4	5–30	0.001

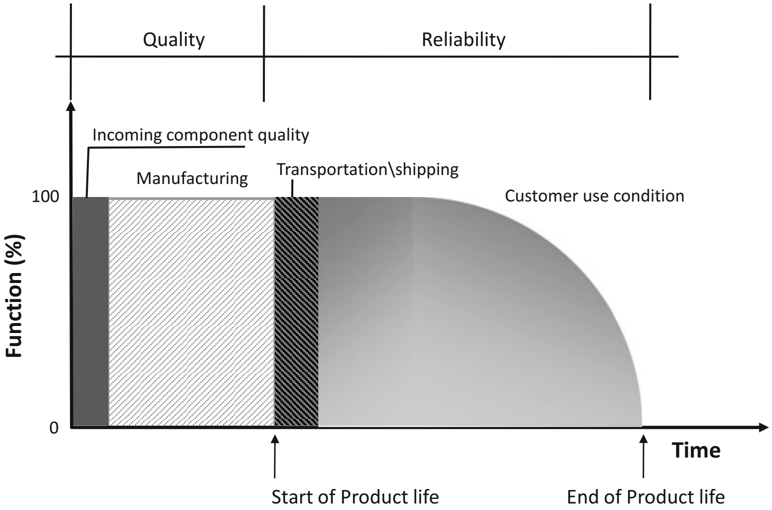


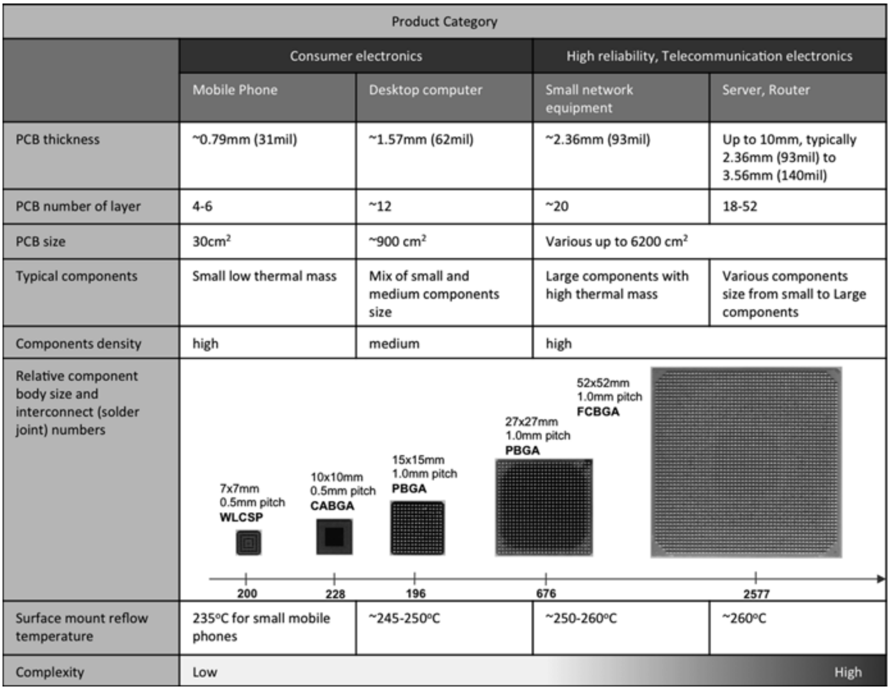
Fig. 1.3 The difference between quality and reliability schematically shown

Before we discuss reliability directly, we often face confusion between quality and reliability. As the definitions state, quality and reliability are different terms with a common ground. Quality is more related to the transition between manufacturing and the beginning of the device life cycle. As shown schematically in Fig. 1.3, a few factors among several that affect quality are the defect rate in the process during assembly and the component quality itself. For example, during assembly of an electronic circuit board with numerous components, either a highly defected group of components or a wrongly calibrated assembly temperature profile can cause a lot of defective boards, which are functionally failed even before sending out to the field. These are considered quality issues and not reliability issues.

Of course, a defective board can escape from the early filtering process and cause failure during early service, but once again this is a quality induced failure, not a reliability issue. Once the product is qualified to be released to the market by passing all the required tests, the life of the product or device begins. As the device functions and is used in their anticipated environment, various mechanisms occur to degrade the device and finally make it fail in a region where the weakest link begins to emerge near the end of life, which is expected by both the designer and the user. Reliability is the more natural behavior of the electronic device or the product if all the construction and quality expectations are met. Thus, it is important to understand the mechanisms that cause the device degradation, in other words, degrade the reliability. Also important is to identify what factors accelerate or decelerate the degradation mechanism to accurately estimate and predict the life and mitigate the unexpected failures.

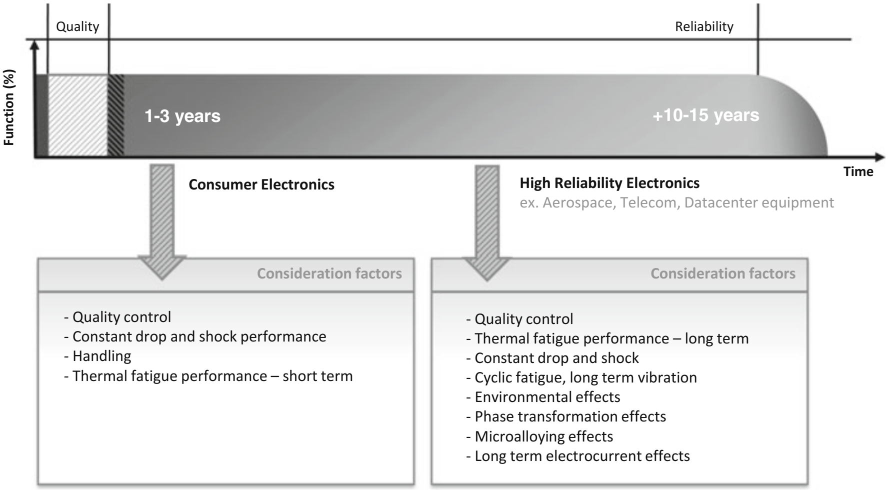
The Scope of This Book: The Book in a Nutshell

We will go deeply into the fundamentals of the solder interconnect reliability from thermal, electrical, mechanical, and chemical aspects, but before that, we will discuss the details of various package types, the structure of the interconnect, and the character and properties of solders. As shown in Fig. 1.4, there are a variety of electronic components in various sizes and configurations. In Chap. 2 we will visit various package types, which face their own challenges whether thermal or mechanical. Small packages have fine pitch and small solder balls attached with a relatively large die to body size ratio, which can impact the thermal cycling performance. Large body size packages are heavy, potentially facing mechanical stability challenges, and some components can reach high temperatures at peak functions, which directly alters the microstructure and the properties of the system and hence, its reliability. Also, the base plane printed circuit board (PCB) in which the components will be assembled varies with size, thickness, and materials used. These impose all kinds of mechanical responses from external factors as shown in Fig. 1.5. As Fig. 1.4 shows, the layer count and the component density varies based on the product applications and thus varies in expected reliability levels. Consumer electronics usually need small form factors with high density to make the product thin, light, and portable. These consumer products actually don't need a very long thermal cycling lifetime but need a very stable mechanical performance since it is portable. On the other hand, the telecommunication sector doesn't need small components, but it needs to accommodate various high-density components in a very good signal integrity package to achieve a high-speed process capability. The thermal cycling needs a very long and reliable performance to function in the field usually for more than 10 years. These products are mostly not handy and portable, but because components are heavy, the product needs to endure shock impacts during transportation and handling. Then there are of course high-reliability products that need everything, like military and harsh environment electronics, with portability, high density, large



Product Category				
	Consumer electronics		High reliability, Telecommunication electronics	
	Mobile Phone	Desktop computer	Small network equipment	Server, Router
PCB thickness	~0.79mm (31mil)	~1.57mm (62mil)	~2.36mm (93mil)	Up to 10mm, typically 2.36mm (93mil) to 3.56mm (140mil)
PCB number of layer	4-6	~12	~20	18-52
PCB size	30cm²	~900 cm²	Various up to 6200 cm²	
Typical components	Small low thermal mass	Mix of small and medium components size	Large components with high thermal mass	Various components size from small to Large components
Components density	high	medium	high	
Relative component body size and interconnect (solder joint) numbers	7x7mm 0.5mm pitch **WLCSP** (200) 10x10mm 0.5mm pitch **CABGA** (228)	15x15mm 1.0mm pitch **PBGA** (196)	27x27mm 1.0mm pitch **PBGA** (676)	52x52mm 1.0mm pitch **FCBGA** (2577)
Surface mount reflow temperature	235°C for small mobile phones	~245-250°C	~250-260°C	~260°C
Complexity	Low			High

Fig. 1.4 The difference between consumer electronic device and high-reliability devices/equipment



- Quality control
- Constant drop and shock performance
- Handling
- Thermal fatigue performance – short term

- Quality control
- Thermal fatigue performance – long term
- Constant drop and shock
- Cyclic fatigue, long term vibration
- Environmental effects
- Phase transformation effects
- Microalloying effects
- Long term electrocurrent effects

Fig. 1.5 Expected reliability for high-reliability products is higher and the expected lifetime is longer than typical consumer electronic products components, shock performance, vibration performance, good thermal cycling performance, etc. Based on their reliability expectations and end-use conditions, there are factors that need to be considered at a higher priority than others. As shown in Fig. 1.5, the diagram shown in Fig. 1.3 can be modified and expanded to include the long-term reliability electronics. There are several additional factors which are not considered for short life electronics but crucial for long-term/high-reliability application products.

What Affects Reliability

Then what kind of factors affects the life of a certain product or component? The variety of end-use conditions, which imposes the external environmental factors, can be seen in a device exposed to an outside environment. The typical climatic weather and day to night cycles produce a characteristic thermal cycle. This external thermal fluctuation also occurs in devices in controlled environments. A server in a very good air-conditioned room also experiences thermal fluctuation because the components are constantly functioning with an on/off state and the junction temperatures increase and decrease based on the feedback control settings of a cooler, which keeps the temperature constant for better functionality. Another easily seen factor is in our everyday handheld devices, where a simple drop can impact the whole device with various shock waves and strain fluctuations, a mechanical factor. Mechanical shock and bend and vibration are a few representative factors that can directly affect the electronic device. More extreme environments can be found in moving vehicles and equipments, which have moving parts in it. Even the hard drive can produce vibration which can affect the mechanical stability of the nearby located interconnects. Another crucial factor, which is probably a core factor in this category, is the effect of current flow. For example, in an interconnect with a high current density, the joule heating occurs and brings the component into a higher temperature state. When combined with a moving vehicle, the complexity can be even more increased if it is, for example, winter outside. We can easily have a multifactor combination of thermal, electrical, mechanical, and even chemical factors that can all affect the reliability of the product or component (e.g., salt and defrost chemicals on the road during winter).

Figure 1.6 summarizes the major external factors in various application products in a few categories. For example, some of the portable consumer products have relatively short lifetime expectancy and are expected to be stable against a few mechanical drop/shock; thus, the thermal fatigue performance doesn’t need to be so much improved as the long-term life expectancy products, in which expected lifetimes are more than 10 years. With the same thought path, a long-term high-reliability product, which sits in a controlled room, does not need an extremely high-shock performance. With these consideration factors and end-use conditions in mind, a design window can be defined. But most important, one should know the mechanisms of how the

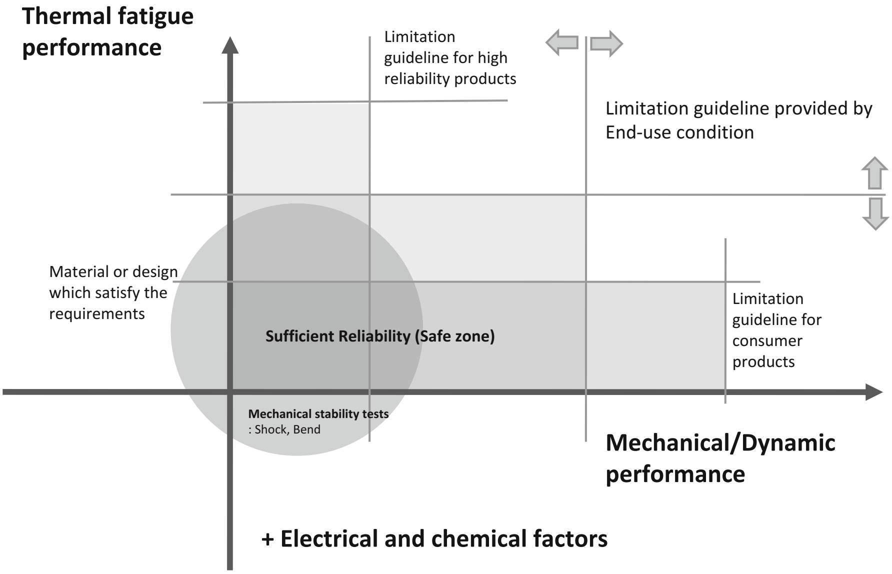


Fig. 1.6 External factors and categorized performance including thermal, mechanical, and electrical/chemical factors

performance interacts with the external end-use conditions. Knowing how and how fast the degradation to failure happens will lead us to the understanding of the degradation/failure mechanism, which ultimately leads us to the right methodology and solution mechanism, which can mitigate and improve the performance one desired.

Reliability Prediction and Improvement

Then how can we estimate or assess whether the reliability is acceptable or not and make improvements if needed? Reliability prediction is the combination of creating a proper reliability model together with estimating and identifying the mechanism, requiring the definition of the input parameters for the model (e.g., failure rates for a particular failure mode or event and the mean time to repair the system for a particular failure) and to provide a system or component interconnect level estimate for the output reliability parameters (e.g., system availability or a particular functional failure frequency). It is realistically impossible to wait until a target component fails and record the failure time to assess the lifetime of a certain device. A more effective and clever way to assess the lifetime in a reasonable manageable time frame is needed without sacrificing time and losing any meaningful data. Thus, accelerated tests are used to identify such parameters.

There are well-established methods and deep analytical strategies which provide various approaches to achieve what we need. One of the strategies is "qualitative tests" and the other is "quantitative test" methods. One additional method is environmental stress screening (ESS) [7]. The goal of ESS is to expose, identify, and eliminate latent defects which cannot be detected by visual inspection or electrical testing but which will cause failures in the field. ESS is performed on the entire product or component and does not involve sampling. A qualitative test method is an accelerated test. Because it shows the failure mode only, it is also called a shake and bake test or highly accelerated life test (HALT) [8]. These methods overstress products to obtain failures as quickly as possible, but the end of the test has no reliability information. Hence, the qualitative test is more commonly applied to a relatively small number of specimens subjected to a harsh environment. If the specimen survives, it passes the test. This test method can give the engineer a benefit of revealing the potential failure modes, but the reliability information is limited, and it is often not clear whether the failure mode observed in this test is really the failure mode that will occur in real service conditions.

Unlike qualitative testing, quantitative accelerated life testing is designed to provide reliability information on the product, component, or system. Time to failure can be in any quantitative measure, such as hours, days, cycles, miles, etc. The easiest and most common form of accelerated life testing is "continuous use acceleration." Accelerated tests can be performed at elevated temperature, humidity, voltage, pressure, vibration, etc., or in a combined manner in order to accelerate the failure mechanism. The stress level should be chosen to accelerate the failure modes under consideration, but the stress levels should be chosen so that they do not introduce failure modes that would never occur under real-use conditions. Also, the stress levels must be high enough so that enough failures are observed within the allowable timeframe. Of course the uncertainty is higher if the accelerated stress is higher than the usual operating stress, but the accelerated life test estimates the distribution of lifetimes in the product in a shorter time, which can identify wear-out periods (defined in the next section) resulting from actual product performance degradation.

How Do We Show and Express the Reliability Level: Weibull Distribution

An illustration on the difference between quality and reliability can be seen in the plot shown in Fig. 1.7, which is often used to describe the lifetime of a product or component called the "bathtub curve." The bathtub curve consists of three periods: an infant mortality period with a decreasing failure rate followed by a normal life period (also known as "useful life") with a low, relatively constant failure rate, concluding with a wear-out period that exhibits an increasing failure rate. The bathtub curve does not depict the failure rate of a single item but describes the relative failure rate of an entire population of products over time. Some individual units will fail relatively early (infant mortality failures), others will last until wear-out, and some will fail

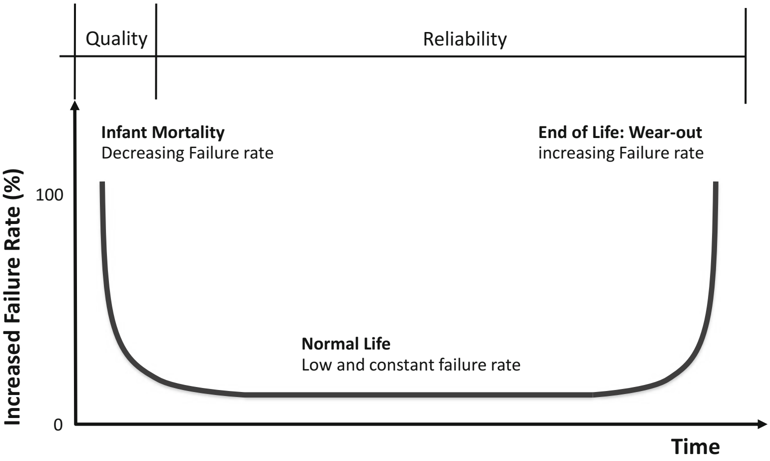


Fig. 1.7 Bathtub *curve*, which shows the three different regions related to infant Mortality, normal life, and wear-out region

during the relatively long, normal life period. Failures during infant mortality are highly undesirable and are always caused by defects and design flaws: material defects, design factors, process factors during assembly, etc., and are considered as quality issues [5]. The infant mortality period is a time when the failure rate is dropping but is undesirable because a significant number of failures occur in a short time. During normal life, it is desired to have the bottom of the bathtub to be as low as possible with a wear-out period long after the expected useful lifetime of the product.

One of the wonders of nature is that even twins have different lifetimes. Variation in unknown and subtle birth conditions as well as differences in lifestyle and specific experiences (such as an injury) makes two twins have different lifetimes. When we consider life expectancy of people, we evaluate it by using statistical analysis of the sample groups and extrapolate it to the entire population. The key to the success of such analysis is the choice of the statistical model that correctly captures lifetime variations among people and also to select sufficient sampling for extracting parameters defining the distribution. The reliability evaluation requires the same type of analysis. It is impractical to test all products under a normal-use condition. The reliability evaluation has to be conducted with a selected number of samples under highly accelerated but relevant conditions for the failure. The test result is then fitted to an appropriate statistical model for extraction of model parameters like a mean and standard deviation. Through extrapolation of the result to end-use condition and entire product population, reliability assessment is completed. The common industrial choice for the statistical analysis of failure is the Weibull model, known as Weibull distribution. Statistical theory behind the model is beyond the scope of this book, yet it can be mentioned that the Weibull distribution physically captures extreme boundary of lifetime rather than the nominal distribution. The choice of

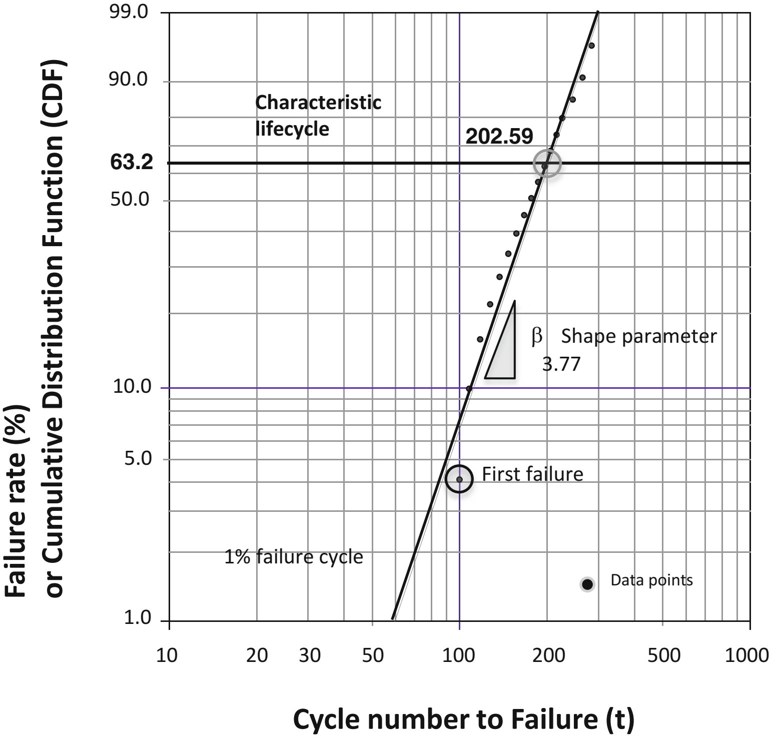


Fig. 1.8 Typical Weibull plot

Weibull may be correct and safe because many physical failure processes are dictated by the weakest link of potential failure sources. For example, fracture toughness of steel wire is known to follow the Weibull distribution because the fracture toughness is determined by the largest crack in the wire. Correlation to physical failure mechanics makes the Weibull distribution a correct choice and thus popular.

The Weibull distribution is a continuous probability distribution used in probability theory and statistics, but it is a useful way to show and see the performance of the device or system. The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with a small number of samples. Another advantage of Weibull analysis is that it provides a simple and useful graphical plot of the failure data. Figure 1.8 is a typical Weibull plot. The horizontal scale is a measure of life or aging. Start/stop cycles, mileage, operating time, landings, or mission cycles are examples of aging parameters. The vertical scale is the cumulative percentage failed. The two defining parameters of the Weibull plot are the slope, beta (β), and the characteristic life, eta (η). The slope of the line, β, is particularly significant and may provide a clue about the physics of the failure process, determines which member of the family of Weibull failure distributions best fits or describes the data, and also indicates which class of failures is present:

$\beta < 1.0$ indicates infant mortality
$\beta = 1.0$ means random failures (independent of age)
$\beta > 1.0$ indicates wear-out failures

The characteristic life, η, is the typical time to failure in Weibull analysis. It is related to the mean time to failure.

The horizontal scale is the cycle or time (t) parameter to failure, with a logarithmic scale. The vertical scale is the cumulative distribution function (CDF) that defines the proportion of the parts that will fail up to cycle number (t) in percent. The statistical symbol for the CDF is $F(t)$, the probability of failure up to time t. The complement of $F(t)$ is reliability, the probability of not failing up to time t. $R(t) = 1 - F(t)$:

$$F(t) = 1 - e - (t/\eta)\beta$$
$$R(t) = e - (t/\eta)\beta$$

where

$F(t)$: fraction failing up to time (t) (CDF)
t: failure time
e: the base for natural logarithms
η: characteristic life or scale parameter
β: slope or shape parameter

The characteristic life η is defined as the age at which 63.2 % of the units will have failed (indicated on the plot with a red line). For $\beta = 1$, the mean time to failure and η are equal. For $\beta > 1.0$, the mean time to failure (MTTF) and η are approximately equal.

Two sets of example plots are shown in Fig. 1.9, where Fig. 1.9a is a data set, which has the same first failure condition but different failure interval after the first failure. The result shows that each data set has its own shape parameter (β), where different shape parameters produce a different characteristic lifetime. With a lower beta slope, the characteristic lifetime occurs at a much higher value than the higher beta slope data set. This means that even with the same first failure cycle number, it is important to see the following failure trend to accurately estimate the life expectancy. Figure 1.9b shows the same beta for each data set, but the first failure is well aligned with the characteristic life cycle number ranking. The meaning of the beta slope parameter is related to the physics of the failure. Thus, the beta differences in Fig. 1.9a represent different failure mechanisms. There are more Weibull plots in this book in the following chapters. Each Weibull plot will provide their unique stories about the test and the sample results. Different failure mechanisms arising from differently evolved microstructures will be discussed.

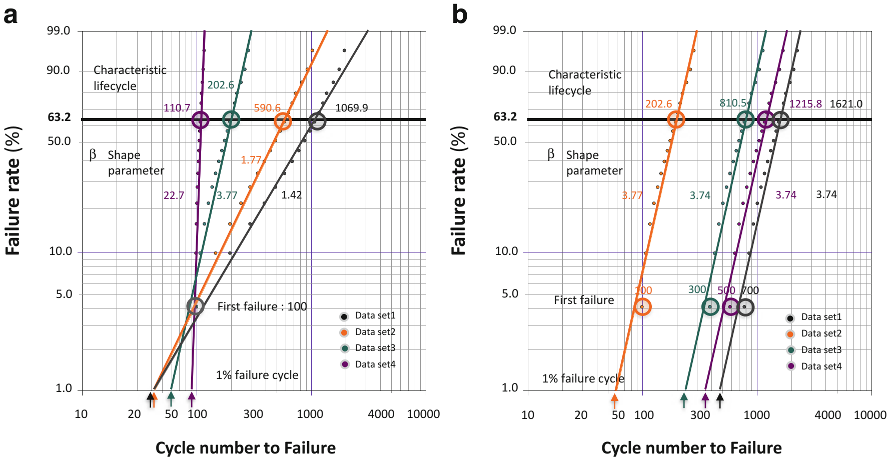


Fig. 1.9 Weibull plots with different data set presentation. (**a**) Fixed first failure but different failure cycle trend resulted in a variety of characteristic life cycle number. (**b**) Different first failure but the follow-up failure with a similar rate shows same beta value

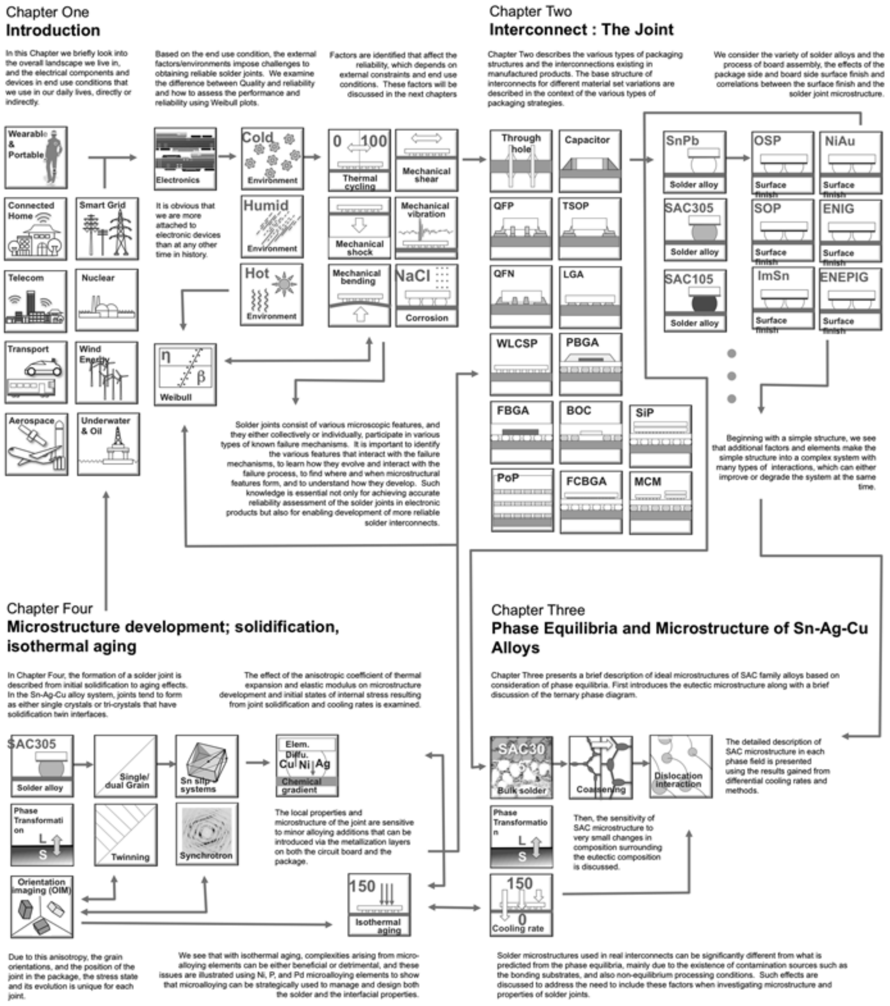
The Role of Microstructure

One of the key questions and steps in the reliability analysis is to ask what makes failure to occur at different rate even within the same sample group. The answer to this question, when it comes to failure in materials, is usually found from what is known as the microstructure. Microstructure does not refer to any specific feature in a material, but rather it is a broadly defined term to include any microscopically distinctive feature that can affect the physical properties of materials. It includes many structural features commonly present in materials including interface, grains and their boundaries, phases, precipitates, crystal defects, and so on. Hence, it can be said that material is a collection of microstructural features, and they are the ones that respond to the environmental conditions such as the stress, temperature, current, etc. Because microstructural details have to vary from one component to the other with subtle variation in the process and chemical condition, materials are bound to have variation in their responses to the external loads and therefore exhibit different failure rates or, in an extreme situation, failure mechanisms. Since microstructure includes so many different elements, it is important to identify the specific element or elements that have direct connection to the failure mechanism under evaluation, which is a major part of reliability engineering. A classic example of such kind may be found from the development of Al alloys. Pure Al has such a low yield strength that it cannot be used for any structural applications. The low yield strength of Al stems largely from the fact that dislocations are highly mobile in pure Al when subjected to stress. Therefore, in order to increase the yield strength, a small amount of alloying elements, most notably Cu and Ti, are added to Al. The addition of those elements results in a formation of small but hard precipitates densely dispersed in Al matrix. Impeded by them, dislocations cannot move very well unless stress is high enough for them to either cut through them or bypass around them. This enables Al alloys to withstand high stress beyond its limit in pure state and to be used for structural applications. In this case, therefore, the relevant microstructure may be the precipitates while their size and distribution can be included in the microstructure.

Sn-rich solder joints, the main topic of this book, is not an exception to this rule. Solder joints consist of various microscopic features, and they, either collectively or individually, participate in various types of known failure mechanisms. Either their presence or absence is responsible for rapid failure or slow failure, and, in some cases, precipitates become a source of failure mechanism. It is therefore important to identify the very features associated with the failure mechanisms, to learn how they evolve and interact with the failure process, to find where and when they form, and to understand the contributing factors to their formation. Such knowledge is essential not only for achieving accurate reliability assessment of the solder joints in electronic products but also for enabling development of more reliable solder interconnects. Even with complexity, there are a few key microstructural features that are known to interact with failure mechanisms such as the constitutional phases and their distribution in the solder matrix, grain structure, and interface structure at the adjoining interfaces. These microstructural features interact with common failure mechanisms including thermal fatigue, mechanical fatigue and shock, and corrosion. This book describes such microstructural features, their origin and evolution, and their interaction with their associated failure mechanisms.

Chapter Summary and the Structure of This Book

As mentioned in the abstract of this chapter, the foundation of this book is that mechanical properties are defined by microstructure and chemical composition [1]. This fundamental approach follows the path of the microstructure evolution and identifies the microstructure interaction with the external environmental factors. With the world covered with more electronic devices and the higher dependency on the signals and output that these devices provide, identifying the elements that react to these external factors is crucial. Since we need to know the degradation mechanism to find the mechanism that causes failures, simultaneously gaining and understanding of microstructural evolution phenomena can lead to improvements in reliability of the solder interconnect and ultimately the device or product. In this chapter we briefly looked into the overall landscape we live in and the electrical components and devices in various end-use conditions we use in our daily lives. In the next chapters, we will start with covering the initial formation of the microstructure and the evolution during time and temperature. Further on, we will identify the factors and explain the mechanisms associated with various end-use conditions and



Chapter One

Introduction

In this Chapter we briefly look into the overall landscape we live in, and the electrical components and devices in end use conditions that we use in our daily lives, directly or indirectly.

Based on the end use condition, the external factors/environments impose challenges to obtaining reliable solder joints. We examine the difference between Quality and reliability and how to assess the performance and reliability using Weibull plots.

Factors are identified that affect the reliability, which depends on external constraints and end use conditions. These factors will be discussed in the next chapters

It is obvious that we are more attached to electronic devices than at any other time in history.

Solder joints consist of various microscopic features, and they either collectively or individually, participate in various types of known failure mechanisms. It is important to identify the various features that interact with the failure mechanisms, to learn how they evolve and interact with the failure process, to find where and when microstructural features form, and to understand how they develop. Such knowledge is essential not only for achieving accurate reliability assessment of the solder joints in electronic products but also for enabling development of more reliable solder interconnects.

Chapter Two

Interconnect : The Joint

Chapter Two describes the various types of packaging structures and the interconnections existing in manufactured products. The base structure of interconnects for different material set variations are described in the context of the various types of packaging strategies.

We consider the variety of solder alloys and the process of board assembly, the effects of the package side and board side surface finish and correlations between the surface finish and the solder joint microstructure.

Beginning with a simple structure, we see that additional factors and elements make the simple structure into a complex system with many types of interactions, which can either improve or degrade the system at the same time.

Chapter Four

Microstructure development; solidification, isothermal aging

In Chapter Four, the formation of a solder joint is described from initial solidification to aging effects. In the Sn-Ag-Cu alloy system, joints tend to form as either single crystals or tri-crystals that have solidification twin interfaces.

The effect of the anisotropic coefficient of thermal expansion and elastic modulus on microstructure development and initial states of internal stress resulting from joint solidification and cooling rates is examined.

The local properties and microstructure of the joint are sensitive to minor alloying additions that can be introduced via the metallization layers on both the circuit board and the package.

Due to this anisotropy, the grain orientations, and the position of the joint in the package, the stress state and its evolution is unique for each joint.

We see that with isothermal aging, complexities arising from micro-alloying elements can be either beneficial or detrimental, and these issues are illustrated using Ni, P, and Pd microalloying elements to show that microalloying can be strategically used to manage and design both the solder and the interfacial properties.

Chapter Three

Phase Equilibria and Microstructure of Sn-Ag-Cu Alloys

Chapter Three presents a brief description of ideal microstructures of SAC family alloys based on consideration of phase equilibria. First introduces the eutectic microstructure along with a brief discussion of the ternary phase diagram.

The detailed description of SAC microstructure in each phase field is presented using the results gained from differential cooling rates and methods.

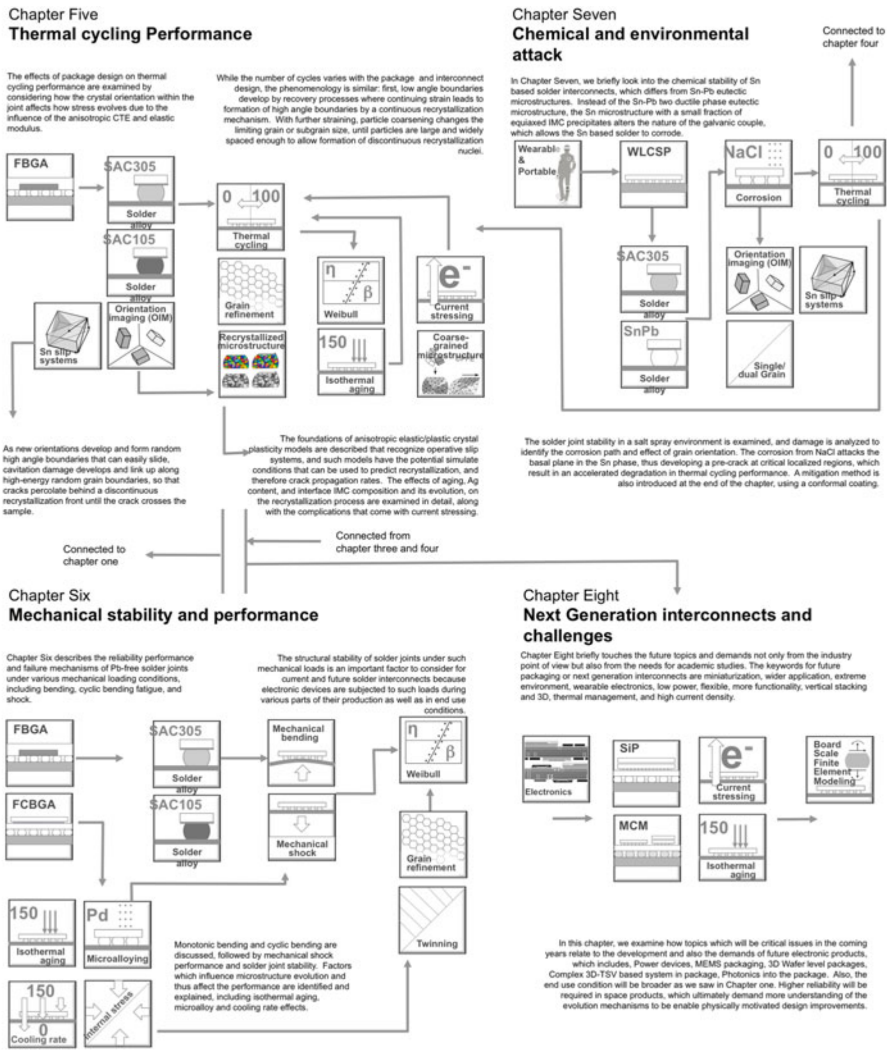
Then, the sensitivity of SAC microstructure to very small changes in composition surrounding the eutectic composition is discussed.

Solder microstructures used in real interconnects can be significantly different from what is predicted from the phase equilibria, mainly due to the existence of contamination sources such as the bonding substrates, and also non-equilibrium processing conditions. Such effects are discussed to address the need to include these factors when investigating microstructure and properties of solder joints.

Fig. 1.10 The whole book in a nutshell. Schematically summarized book outline and content

external factors, which includes thermal, mechanical, and chemical performances. Figure 1.10 shows the overall structure of this book schematically in a very brief and simplified format.

Chapter 2 describes the various types of packaging structures and the interconnections present in industrial products. It also provides the basic structure of interconnects for each material set variation and describes the various types of packaging structures and the interconnections. We will examine the variety of solder alloys and the process of board assembly, the effect of the package-side and board-side surface finish, and the correlation between the surface finish and the solder joint microstructure.



Chapter Five
Thermal cycling Performance

The effects of package design on thermal cycling performance are examined by considering how the crystal orientation within the joint affects how stress evolves due to the influence of the anisotropic CTE and elastic modulus.

While the number of cycles varies with the package and interconnect design, the phenomenology is similar: first, low angle boundaries develop by recovery processes where continuing strain leads to formation of high angle boundaries by a continuous recrystallization mechanism. With further straining, particle coarsening changes the limiting grain or subgrain size, until particles are large and widely spaced enough to allow formation of discontinuous recrystallization nuclei.

As new orientations develop and form random high angle boundaries that can easily slide, cavitation damage develops and link up along high-energy random grain boundaries, so that cracks percolate behind a discontinuous recrystallization front until the crack crosses the sample.

The foundations of anisotropic elastic/plastic crystal plasticity models are described that recognize operative slip systems, and such models have the potential simulate conditions that can be used to predict recrystallization, and therefore crack propagation rates. The effects of aging, Ag content, and interface IMC composition and its evolution, on the recrystallization process are examined in detail, along with the complications that come with current stressing.

Chapter Seven
Chemical and environmental attack

In Chapter Seven, we briefly look into the chemical stability of Sn based solder interconnects, which differs from Sn-Pb eutectic microstructures. Instead of the Sn-Pb two ductile phase eutectic microstructure, the Sn microstructure with a small fraction of equiaxed IMC precipitates alters the nature of the galvanic couple, which allows the Sn based solder to corrode.

The solder joint stability in a salt spray environment is examined, and damage is analyzed to identify the corrosion path and effect of grain orientation. The corrosion from NaCl attacks the basal plane in the Sn phase, thus developing a pre-crack at critical localized regions, which result in an accelerated degradation in thermal cycling performance. A mitigation method is also introduced at the end of the chapter, using a conformal coating.

Chapter Six
Mechanical stability and performance

Chapter Six describes the reliability performance and failure mechanisms of Pb-free solder joints under various mechanical loading conditions, including bending, cyclic bending fatigue, and shock.

The structural stability of solder joints under such mechanical loads is an important factor to consider for current and future solder interconnects because electronic devices are subjected to such loads during various parts of their production as well as in end use conditions.

Monotonic bending and cyclic bending are discussed, followed by mechanical shock performance and solder joint stability. Factors which influence microstructure evolution and thus affect the performance are identified and explained, including isothermal aging, microalloy and cooling rate effects.

Chapter Eight
Next Generation interconnects and challenges

Chapter Eight briefly touches the future topics and demands not only from the industry point of view but also from the needs for academic studies. The keywords for future packaging or next generation interconnects are miniaturization, wider application, extreme environment, wearable electronics, low power, flexible, more functionality, vertical stacking and 3D, thermal management, and high current density.

In this chapter, we examine how topics which will be critical issues in the coming years relate to the development and also the demands of future electronic products, which includes, Power devices, MEMS packaging, 3D Wafer level packages, Complex 3D-TSV based system in package, Photonics into the package. Also, the end use condition will be broader as we saw in Chapter one. Higher reliability will be required in space products, which ultimately demand more understanding of the evolution mechanisms to be enable physically motivated design improvements.

Fig. 1.10 (continued)

Beginning with a simple structure, we will see that additional factors and elements make the simple structure into a complex system with various interdependencies, which can improve or degrade the joint at the same time.

Chapter 3 presents a brief description of ideal microstructures of Sn–Ag–Cu family alloys based on consideration of phase equilibria. It first introduces the eutectic microstructure along with a brief discussion of the ternary phase diagram. Then, the sensitivity of Sn–Ag–Cu microstructure on very small changes in composition surrounding the eutectic composition is discussed. The microstructural sensitivity of the alloy composition stems from the fact that there are six possible phase fields for the primary phase formation. The primary phase refers to the phase that is in equilibrium with the liquid phase at off-eutectic composition and is the phase that forms prior to the eutectic reaction during solidification. A detailed description of Sn–Ag–Cu microstructure in each phase field is presented using the results gained from the differential cooling method. Solder microstructures used in real interconnects can be significantly different from what is predicted from the phase equilibria mainly due to the existence of many contamination sources, including the joining substrates and nonequilibrium processing conditions. Such effects are discussed to address the need for their inclusion in investigating microstructure and properties of solder joints of interest. This chapter sets the foundation on which nonequilibrium microstructures that form in practical joints can be understood in Chap. 4.

In Chap. 4, the formation of a solder joint is described from initial solidification to aging effects. In the Sn–Ag–Cu alloy system, joints tend to form as either single crystals or tri-crystals that have twin interfaces that ideally form a "beach ball" orientation relationship of 60° sections about a common crystal [100] axis. The effect of the anisotropic coefficient of thermal expansion and elastic modulus on microstructure development and initial states of internal stress as the joint solidifies and cools is examined. Due to this anisotropy and the grain orientations, the position of the joint in the package, the stress state, and its evolution are unique for each joint. The local properties and microstructure of the joint are sensitive to minor alloying additions that can be introduced via the metallization layers on both the circuit board and the package. We will see that with isothermal aging, complexities arising from microalloying elements can be either beneficial or detrimental, and these issues are illustrated following Ni, P, and Pd microalloying elements to show that microalloying can be strategically used to manage and design both the solder and the interfacial properties.

In Chap. 5, the effects of package design on thermal cycling performance are examined by considering how the crystal orientation within the joint affects how stress evolves due to the influence of the anisotropic CTE and elastic modulus. With low-stress designs such as plastic ball grid arrays (PBGA, larger balls with a large pitch), it takes thousands of cycles before cracks are prevalent, while direct chip attachment designs such as wafer-level chip-scale packages (WLCSP) will fail in a few hundred cycles. While the number of cycles varies with design, the phenomenology is similar: first, low-angle boundaries develop by recovery processes where continuing strain leads to the formation of high-angle boundaries by a continuous recrystallization mechanism. With further straining, particle coarsening changes the limiting grain or subgrain size, until particles are large and widely spaced enough to allow discontinuous recrystallization nuclei to form. As these new orientations develop and form random high-angle boundaries that can easily slide, cavitation damage develops which links up along high-energy random grain boundaries, so that cracks percolate behind a discontinuous recrystallization front until the crack crosses the sample. The foundations of anisotropic elastic/plastic crystal plasticity models are described that recognize operative slip systems, and such models have the potential simulate conditions that can be used to predict recrystallization. The effects of aging, interface IMC composition and evolution, and Ag content on the recrystallization process are examined in detail, along with the complications that come with current stressing.

Chapter 6 describes the reliability performance and failure mechanisms of Pb-free solder joints under various mechanical load conditions, including bending, cyclic bending fatigue, and shock. The structural stability of solder joints under such mechanical loads is an important factor for the current and future solder interconnects because electronic devices are subjected to such loads during various parts of their production as well as in end-use conditions. Even more importantly, mechanical stability is emerging as critical reliability concern with a rapid expansion of mobile electronics. In order to properly apprehend their threats to the reliability, this chapter describes the threat from each mechanical load and the mechanism by which the solder joint fails. We begin with failure in solder interconnects induced by bending forces on a PCB. The source of the bending force and its test method is presented along with the discussion on failure mechanism. It is shown that the failure by bending force occurs either in the Cu trace in PCB or solder/Cu interface. Secondly, the influence of cyclic bending fatigue is introduced. It is discussed more in terms of its mechanics and its potential as a new reliability evaluation methodology. Finally, failure by mechanical shock is discussed with weighted emphasis on recent experimental observations showing a sensitivity of shock resistance to the microstructure of SAC solder joint.

In Chap. 7, we will briefly look into the chemical stability of the Sn-based solder interconnects. Sn itself is considered as a good corrosion-resistant material. In early use of the eutectic Sn–Pb alloy in electronics, not much research was performed since there was no specific corrosion concern. But with the microstructure change from a dual-phase eutectic structure to a Sn microstructure with equiaxed IMC precipitate islands, a potential galvanic couple is formed, which enables Sn-based solder to corrode. The solder joint stability in a salt spray environment is examined, and damage is analyzed to identify the corrosion path and effect of grain orientation. The corrosion due to NaCl attacks the basal plane in the Sn, thus developing a pre-crack at critical localized regions, which results in an accelerated degradation in thermal cycling performance. A mitigation method is also introduced at the end of the chapter, using conformal coating.

Finally in Chap. 8 we will briefly touch the future topics and demands not only from the industry point of view but also from the perspective of academic research opportunities. The keywords for future packaging or next-generation interconnects are miniaturization, wider application, extreme environment, wearable electronics, low power, flexible, more functionality, vertical stacking and 3D architecture, thermal management, and high current density. In this chapter, we will go through a list of topics which will be critical issues in the coming years related to the development and demands of future electronic products, which includes power devices, MEMS packaging, 3D wafer-level packages, complex 3D-TSV-based system in package, and photonics in the package. Also, the end-use condition will be broadened as we saw in this chapter. Higher reliability will be required in consumer space products, which ultimately demands more understanding of the solder joint evolution mechanisms to enable rational strategies for improvement.

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