Reliability Study of Subsea Electronic Systems Subjected to Accelerated Thermal Cycle Ageing

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***Abstract*— Reliability is of increasing importance for electronics systems operating at harsh environments, such as the electronic telecommunication systems used at subsea level. The aim of this research was to investigate the reliability of such electronic systems through a simulated accelerated thermal cycle test. The paper presents a step-by-step process of designing accelerated thermal cycle test using field operating conditions. The Coffin-Mansion equation was used to calculate the accelerated factor for the thermal cycle test. In order to simulate the expected life time of 25 years, the solder assembly samples were subjected to 400 temperature cycles, with every cycle lasting for 40 minutes. Reliability was determined by measuring shear strengths of solder joints of different electronic components at set intervals. Although some of the components showed an initial decrease in shear strength, it was generally concluded that the electronic assemblies are able to maintain their shear strength for up to 25 years. The fracture surfaces of the solder joints, after shear testing, were also analyzed for brittle and ductile fractures, with the use of scanning electron microscopy (SEM).**

***Index Terms*—Reliability, Solder Joint, Shear Strength, Fractures.**

I. Introduction

In the current global competitive market it is crucial to make highly reliable products. This in turn will reduce product cost by having less warranty claims and low repair costs. Furthermore, in some application areas such as under water locations it is impossible or rather unaffordable to repair or change a faulty component.

The solder joints are the weakest part of an electronics manufacturing assembly. Due to this it is important to ensure that the solder joints are reliable for the expected lifetime of the assembly. In this research study accelerated ageing of the product by thermal cycling was used to investigate solder joint reliability. Accelerated life testing is still a relatively new subject in reliability engineering, but it is starting to gain greater acceptance in the industry. Forcing the product to fail quickly reduces test time and still allows understanding of the life characteristics of products. The main focus of this research was to study the reliability of electronic telecommunication products that operates at the ground of the Atlantic Ocean. The objectives of the study are three-fold: to design accelerated thermal cycling tests by taking account of operating conditions and expected product life time; to evaluate the shear strength of solder joints for different surface mount components, at different stages of thermal cycling; and to examine the shear-fractured board surface for brittle and ductile fractures using scanning electron microscope.

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II. Materials and Experimentation

A. Materials

The electronic assemblies used for this investigation are designed and developed for operation at the ground of the Atlantic Ocean, where these are used as hubs for joining different cables for telephone connections.

The solder joints between the electronic components and printed circuit boards (PCBs) were produced from a lead-free solder paste with solder alloy composition of 95.5% Tin 3.8% Silver 0.7% Coppper and melting point of 217 °C.

B. Field conditions

The temperature at the ground of the Atlantic Ocean is nearly constant at around 2 °C. However, the electronic systems laid on the ocean bed are continuously producing heat while they are running, heating up the PCB board and also the solder joints. Cooling system is therefore, used around the electronic units to avoid any drastic increase in temperature. Within the cooling system the electronic components experience very small variation in temperature (between 25 °C and 30 °C). However, considering the worst case scenario, it is estimated that electronic components (and hence the solder joints) undergo a cyclic change in temperature from 20 °C to 35 °C with a cycle time of 1 hour. The electronic systems are working nearly the whole year and switched off only once or twice a year. For cycle time calculations only the working period was used, the case of switching off the unit is neglected.

C. Thermal Cycling

In order to simulate temperature cycles in the field, the electronic systems were subjected to accelerated thermal cycling. Temperature cycling test is one of the most important tests used to assess the reliability of solder joint interconnections. The objective of temperature cycling test is to assess the resistance and robustness of the package structure to exposures at extremes of high and low temperatures and to the effect of alternate exposures to these extremes [1].

In order to define the thermal cycling parameters the following standards were looked at: IPC-9701 [2], IPC-SM-

785 [3] and JESD22-A104-B [4]. The standards suggest low and high thermal cycle temperatures of 0 to 100° C respectively to induce fatigue damage to the solder joints. It is also suggested that the changes in temperature should be at rates less than 20° C/min to avoid thermal shock [3]. Dwell times of 5, 10 or 15 min are generally used for solder fatigue and creep testing [4]. Based on the guidelines from the standards and literatures, thermal cycle parameter values are identified and these are presented in table I. The duration for one thermal cycle results from the elected parameters is 40 min. A visual presentation of the designed thermal cycle profile is shown in Fig. 1.

TABLE I
THERMAL CYCLING TEST PARAMETERS

Low Temperature (°C)	0
High Temperature (°C)	100
Ramp Rate (°C/min)	10° C/min
Dwell Time (min)	10
Cycle Period (min)	40

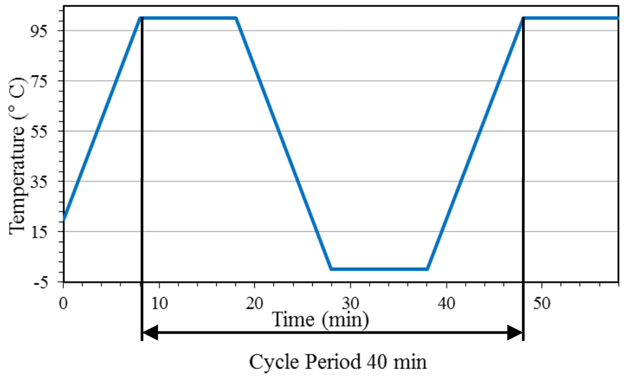

Fig. 1. Thermal Cycling Profile

The useful life of the electronic systems was estimated to be a minimum of 25 years. In order to calculate the thermal cycle test time, acceleration factor (AF) was determined using the Coffin-Mansion equation (1) [5].The necessary parameters to calculate the AF are summarized in table II, based on ref [5].

$$AF = \left(\frac{f_{field}}{f_{test}}\right)^{-m} \cdot \left(\frac{\Delta T_{field}}{\Delta T_{test}}\right)^{-n} \cdot \left[e^{\frac{Ea}{k}\cdot\left(\frac{1}{T_{max,field}} - \frac{1}{T_{max,test}}\right)}\right] \quad (1)$$

Where, AF = acceleration factor, Ea = activation energy in electron-volts (eV), k = Bolzman constant (= 8.617×10^{-5} eV/K), e = 2.71828 (base of the natural logarithms), f_{field} = cycle frequency in the field (cycles/24 hours), f_{test} = cycle frequency in the lab, ΔT_{field} = field temperature difference, ΔT_{test} = lab temperature difference, $T_{max,field}$ = maximum field temperature, $T_{max,test}$ = maximum test temperature.

Upon substituting the parameter values in (1), AF equates to 545.88. Again, AF also equates to the proportion of the number of field temperature cycles to the number of test temperature cycles (see (2)).

TABLE II
VALUES OF COFFIN-MANSON EQUATION PARAMETERS

Parameter	Value
m	0.136
n	2.65
Ea/k	2185
f_{field}	24 cycles/24 h
f_{test}	36 cycles/24 h
ΔT_{field}	15 K
ΔT_{test}	100 K
$T_{max,\ field}$	373 K
$T_{max,\ test}$	308 K

$$AF = \frac{N_{field}}{N_{test}} \quad (2)$$

Where, N_{field} = number of field temperature cycles and N_{test} = number of test temperature cycles. The cycles in the field (N_{field}) can be calculated using (3).

$$N_{field} = t_{field} \cdot f_{field} \quad (3)$$

Where, f_{field} = cycle frequency in the field, t_{field} = time in the field. Equations (2) and (3) were used to calculate the analogous number of test temperature cycles (N_{test}). Finally, the total test times (t_{test}) needed to simulate the filed time (t_{field}) was found out using (4), where t_{cycle} is the time for one cycle.

$$t_{test} = \frac{N_{test}}{t_{cycle}} \quad (3)$$

The calculated values of different parameters are summarized in table III which shows the test times (in hours and days) for different field times (in years). For example, a field time 25 years is equivalent to 10.96 days of test time. Eight electronic PCB samples were used for the investigations, each representing different field times (from 0 to 25 years). The first sample board was used as reference sample and was not subjected to any thermal cycle ageing. The other seven boards were subjected to thermal cycles and taken out of the thermal chamber after different periods of test time as provided in table III. The temperature cycling tests were conducted in an environmental test chamber from Design Environmental (UK) (model FS800-70SV).

TABLE III
PREDICTED TEST TIME

t_{field} (year)	N_{field}	N_{test}	t_{test} (hour)	t_{test} (days)
0	0	0.00	0.00	0.00
2	17520	31.57	21.05	0.88
4	35040	63.15	42.10	1.75
6	52560	94.72	63.15	2.63
10	87600	157.87	105.25	4.39
15	131400	236.81	157.87	6.58
20	175200	315.74	210.49	8.77
25	219000	394.68	263.12	10.96

The thermal cycling profile (as in table I and fig. 1) was programmed with a software tool "HanseView" for up to 10.96 days. Fig. 2 and 3 show the variation in Air and Product temperatures as compared to the programmed temperature. The variation was within an acceptable tolerance of ±5 °C. The solder joints were not able to follow these quick temperature variations because of their thermal time lag. Hence the small variations had a negligible impact on the overall accelerated aging process.

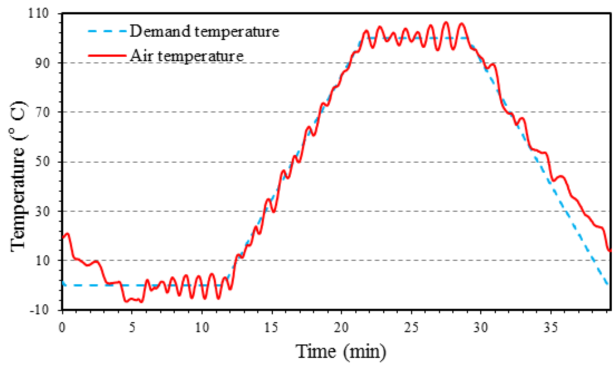

Fig. 2. Deviation of air temperature from demand temperature inside the thermal chamber

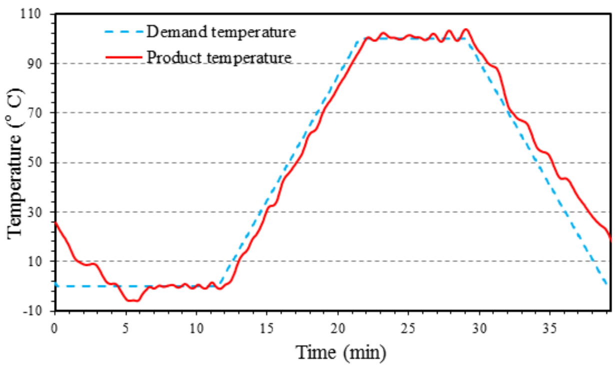

Fig. 3. Deviation of product temperature from demand temperature inside the thermal chamber

All eight PCBs were of same size and each of them were populated with many different types of electronic. After a careful screening, five different electronics components, which were common in all PCBs, were chosen for shear testing and SEM analysis. The standard sizes of these components are provided in table IV.

TABLE IV
DIMENSIONS OF CHOSEN ELECTRONIC COMPONENTS

Size	Length (mm)	Width (mm)	Area (mm^2)
0603 (Res.)	1.55	0.8	0.24
0603 (Cap.)	1.6	0.8	0.28
0805 (Cap.)	2.01	1.25	0.625
1206 (Res.)	3.2	1.6	0.8
1210 (Cap.)	3.2	2.5	1.25
1812 (Cap.)	4.5	3.2	1.6

Res. = Resistor and Cap. = Capacitor.

Reliability of solder joints was tested by measuring the shear strength of the joints. The ball-shear tests were carried out using a 4000 series Dage Bond Tester. The shear speed and shear height (shear tool offset) were kept at 0.7 mm/sec and 0.1 mm respectively for all the electronic components. The fractured surfaces were investigated for brittle and ductile fractures under a scanning electron microscope (SEM). NeoScope JEM-5000 a product of JEOL was used for SEM analysis.

III. Results and Discussions

A. *Study of the effect of accelerated thermal cycle ageing on solder joints*

In order to prepare the PCBs for the shear test a lot of devices which were not chosen for shear tests had to be removed from the boards to make space for shear testing. Also the PCBs were cut into small pieces to provide the opportunity to fix them at the bench vice. During these preparations some of the selected components were damaged. It was also not possible to make enough space to investigate all of the components as planned.

From the shear tests, the ultimate shear force required to rupture the solder joints were recorded and then plotted as a function of field time (in years). For each of the five component types a number of components were sheared for any particular board and the average shear force value was taken. Fig. 4 shows the average shear forces as a function of field time and the deviations for 0603 resistors. The average shear force values were calculated for components in the same way and plotted in fig. 5.The variations in shear force (as in fig. 4) could primarily be due to inconsistency in the amount of solder paste used during reflow soldering. In deed previous research found that stencil printing (used for depositing solder paste) accounts for more than 60% of solder joint assembly defects [6].

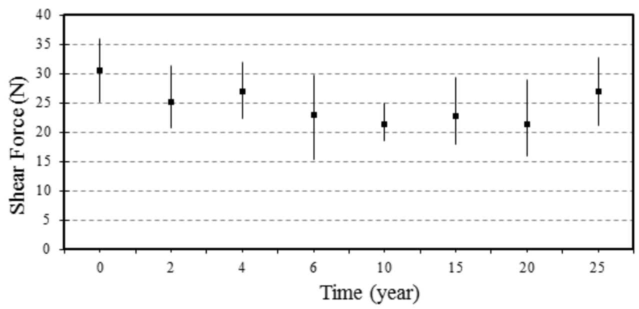

Fig. 4. Mean and deviations of measured shear force values for 0603 capacitors.

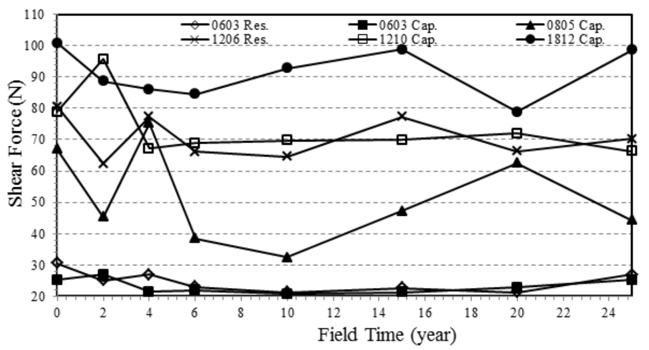

Fig. 5. Shear force as a function of field time

From fig. 5 it is quite clear that the different components produced different level of shear force values. This was expected, as the shear force values are depended on solder shear area and hence smaller components will produce lower shear force and vice versa. The aim of this investigation was to find out if the solder joints degrade over time in the field. A careful observation of fig. 5 reveals that some of the components did show an initial decrease in shear force values. In some instances the shear force values were found to increase as well. However, the decrease or increase in shear values were minimal and hence it can be generally stated that the shear force values remained same within a close limit. Therefore, from the shear test results it can be concluded that the solder joints and the components are mechanically reliable for the expected field time of 25 years.

Shear strengths of the solder joints were calculated by dividing the shear forces with their respective areas. These are plotted in fig. 6. From the plot it is worth noting that that shear strength of the components are not similar. So, depending on the components, some of them are definitely stronger than the others. A similar trend like the shear forces (shown in fig. 5) was observed. Some components did show a decrease in shear strength with time. For example, shear strength of 0603 resistors decreased up until 20 year of field time and showed a sudden increase at 25 years. However, considering the other components, once again it can be said that the components will maintain their mechanical integrity for the expected life of 25 years. The measured shear values are comparable with similar research results reported in literature [7].

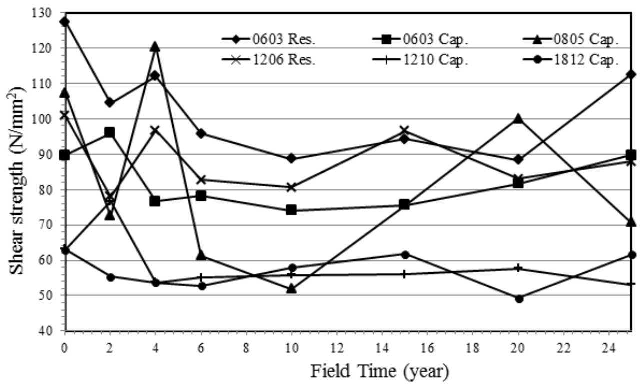

Fig. 6. Shear strength as a function of field time.

B. *Study of Solder Fracture Surfaces*

The microstructure of the fractured solder joints were analyzed using SEM. Before looking into the SEM images it is worth mentioning that the shear fractures could have been affected by the shear heights of the shear tool. The shear tester does not allow ‘on contact’ shear and as mentioned earlier, during shear test the shear tool was set at a height of 0.1 mm above the PCB substrate surface. However, as the shear heights were kept constant for all measurements, the shear fractured surfaces are definitely comparable.

The fracture behaviors of solder joints are very complex in nature. For example, depending on the intensity and speed of applied load solder balls could fail through pad lift, interfacial fracture (solder /intermetallic or intermetallic/pad) and bulk solder failure [8]. Among these failures interfacial fractures are predominantly brittle and bulk solder fractures are tend to be ductile in nature. However, solder ball failure through mixed fractures are also frequently observed by various researchers [8, 9].

In general the fractured surfaces showed a mixed mode of fractures including brittle and ductile fractures. However, in most cases the ductile fracture dominates and there was no specific trend of increasing the brittle fracture according to the stages of thermal cycling. Fig. 7 - 9 show examples of SEM images of fractured surfaces of different components at various stages of thermal cycle ageing. All the fractured surface images were of the PCB side of the joints.

Fig. 7 shows an example of a fracture surface for 1812 capacitor representing 15 years in filed. Ductile fracture is dominated in this case and is evidenced through the presence of dimpled, cup and cone features on the surface. Typical ductile fracture may also have a grey, fibrous appearance and occurs when metal and their alloys are tear off after significant plastic deformation

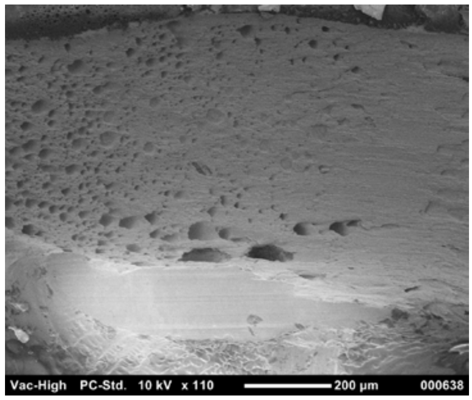

Fig. 7. Fracture surface of 1812 capacitor after 15 years of simulated field time.

Brittle fracture on the other hand, displays either cleavage (trans-granular) or inter-granular fracture. This depends upon whether the grain boundaries are stronger or weaker than the grains. Brittle fracture is characterized by rapid crack propagation with low energy release and without significant plastic deformation. The fracture may have a bright granular appearance. The fractures are generally of the flat type and chevron patterns may be present [10]. Fig. 8 shows the fractured surface of 1210 capacitor representing 6 years in service. In this instance brittle fracture is dominated with the presence of inter-granular fracture features.

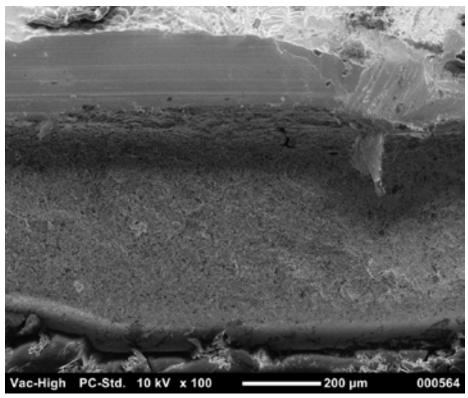

Fig. 8. Fracture surface of 1210 capacitor after 6 years of simulated field time.

Fig. 9 presents the fractured surface for 1812 capacitor after 25 years in service. The presence of both brittle and ductile fractures is evidenced in this case. The dimpled and cups, typical for the ductile fracture can be seen and the inter-granular cleavage, typical for the brittle fracture can be seen as well. As stated earlier observation of fracture surfaces revealed no significant change of the microstructure of the solder joints with ageing time. Just as the shear test results showed, the SEM analysis shows that the solder joints are reliable for the expected field time of 25 years.

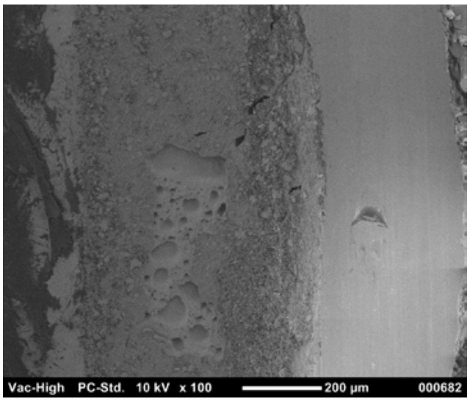

Fig. 9. Fracture surface of 1812 capacitor after 25 years of simulated field time.

IV. Conclusion

The paper investigated the quality and reliability of the solder joints on specific PCBs used for electrical connection at the ground of the Atlantic Ocean. Repair and replacement of these subsea electronic systems is very difficult and would be very expensive. Based on an expected useful life of 25 years an accelerated thermal cycle test was designed to measure the reliability of these devices. Using an accelerated factor, the 25 year of field time was reduced down to 10.96 days in lab test time. Shear testing and SEM analysis of different components were used to ascertain their reliability at different stages of thermal cycling. The results of the shear test show a slight decrease in shear strength but there is no significant decrease in the values observed. During the SEM examination of the shear-fractured board surface, both brittle and ductile fracture modes were observed with ductile fracture being dominated. However, no significant change at the fracture microstructure was observed with thermal cycle ageing. Both the shear test and the SEM analysis showed that the solder joints and the electronic systems are mechanically reliable for the expected lifetime of 25 years.

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