Optimizing Thermo-Mechanical Reliability of Components with Flat Gull Wing Leads

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Abstract

IPC J-STD-001F and IPC-A-610F require a minimum Heel Fillet Height (F) for Flat Gull Wing Leads of solder thickness (G) plus lead thickness (T) for Class 3 products. [1] It is shown in this work that this requirement prevents a solder joint geometry from being optimized for reliability especially under temperature cycling. Therefore, a reconsideration of the Class 3 criterion is proposed in this work.

Temperature cycling tests in combination with finite element (FE) modeling have shown that there is an optimal solder volume to achieve optimum TCoB (temperature cycling on board) performance. On the one hand, increasing the solder volume beyond this optimum results in considerably more solder wetting of the pin shaft and thereby induces a stiffening effect on the gull wing lead. This effect results in higher stresses in the critical cross section area of the solder joint and thereby leads to a reduced solder joint lifetime in temperature cycling. On the other hand, reducing the solder volume results in a (too) small connection area and thereby reduces the solder joint lifetime. Balancing these two counteracting effects of solder volume on TCoB performance enables optimum product reliability.

The current IPC Class 3 criterion in combination with process tolerances requires a nominal solder volume in design that is above the described optimum. Therefore a reduction of the minimum heel fillet height is proposed to enable a robust and optimum solder joint reliability for future products.

It can be shown that the proposed change in solder joint design has a positive effect on product reliability concerning different loading conditions and failure modes as well.

Introduction

Electronic packages with Gull Wing Leads represent a package type widely used in applications with high reliability requirements. One example arequad flat packages, in the following noted as QFPs,which provide the main advantages of high resistivity to thermo-mechanical loads and relatively low cost.

The requirements to solder joint reliability under thermo-mechanical loading conditions are expected to increase in the future for several applications. One example are elevated temperatures in automotive applications due to mounting of the ECUs in harsher environment locations or increasing current densities resulting from major trends like miniaturization and electrification.To ensure product reliability over lifetime an optimization of all influencing parameters is necessary. This includes aspects like package geometry and materials, soldering process parameters and the printed circuit board (PCB).

Some of these aspects have been investigated in detail already. Most studies concentrate either on the package parameters like material selection and geometry or on the shape of the gull wing. A comprehensive model describing the influence of package size, materials, thermal cyclingtemperature profile and exposed pad versus non-exposed pad type is presented by Niessner et al. [2] Other researchers have focused on the influence of the shape of the gull wing lead. All models show a high influence of the pin stiffness onto stresses and strains in the solder joint. Basically it is concluded that with increasing stiffness of the pin the solder joint lifetime in temperature cycling decreases. [3, 4]

Besides thermal cycling other loading conditions influencing the reliability of components with gull wing lead include vibration, mechanical shock and environmental aspects like humidity. [5]

Quality criteria for flat gull wing lead solder joints

IPC J-STD-001F, chapter 7.5.7 and IPC A-610F, Chapter 8.3.5.6 define requirements and acceptance criteria for flat gull wing lead solder joints. Criteria can be divided into positioning of the pin on the PCB pad and criteria for dimensions of the solder joint. A Class 3 solder joint is expected to provide higher quality than a lower class solder joint especially focusing on reliability of the solder joint in harsh environmental conditions. All criteria except for maximum heel fillet height define minimum criteria for specific solder joint dimensions. This basically suggests that an increase in solder volume results in a higher lifetime of the solder joint. In this paper it is shown that this assumption is not valid for packages with flat gull wing leads. The criterion in focus is the minimum heel fillet height as summarized in Table 1.

Table 1 – Requirements for minimum heel fillet height from J-STD-001F [1] and IPC A-610F [6]

Feature		Class 1	Class 2	Class 3
Minimum Heel Fillet Height (Dimension F)	(T) ≤ 0.4 mm [0.015 in]	Wetting is evident	(G) + (T)	(G) + (T)
	(T) > 0.4 mm [0.015 in]		(G) + 50% (T)	

Class 3 requires for high performance/harsh environment electronic products a minimum heel fillet height (F) equal to the solder thickness (G) plus lead thickness (T). Geometrical dimensions are defined in Fig.1.

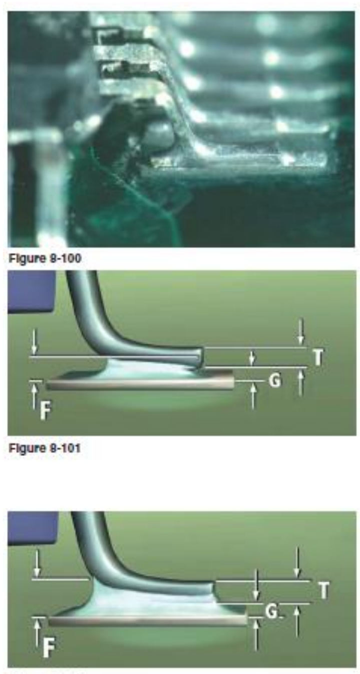


Figure 1 –Excerpt from IPC A-610F: Geometrical dimensions of flat gull wing lead solder joint [6]

Model based approach on the influence of solder volume on solder joint reliability

The degradation of solder joints under thermo-mechanical loading is predominantly induced by the CTE-mismatch between PCB and component. For simplification in the following a calculation for a QFP package is provided as an example. The basic conclusions are also valid for other package types with gull wing leads. QFP components typically consist of a Cu lead frame supporting a Si die which is covered by a molding compound. A schematic drawing including typical coefficients of thermal expansion (CTE) of each material is plotted in Fig. 2.

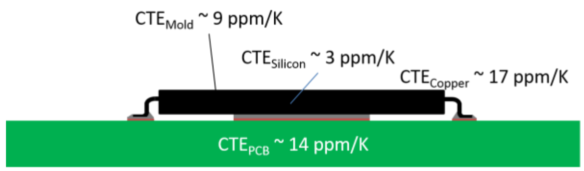


Figure 2 – Schematic drawing of Quad Flat Package soldered on a PCB

The overall in-plane CTE of the QFP component can be approximated based on the lamination theory [7]. For a typical QFP this results in approximately 11 ppm/K. The PCB in contrast has a slightly higher CTE of approx. 14 ppm/K leading to a relative deformation ΔL of the two parts under temperature changes. Due to the much higher relative cross section areas of the component body and PCB compared to the pins/solder joints, most of this deformation has to be covered by the subsystem pin / solder joint. For the following calculations the PCB and QFP body are assumed to be ideally stiff.

In the subsystem pin / solder joint this deformation will be covered by bending deformation Δl_{Pin} of the free gull wing pin and plastic deformation ε_{Solder} of the solder joint as shown in Fig. 3. The load distribution between these two design elements will be defined by each stiffness reaction to the deformation.

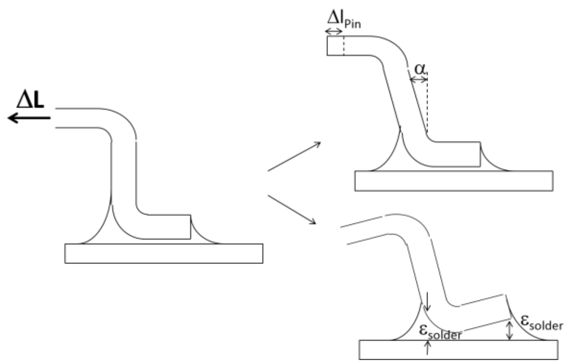


Figure 3 – Deformation of pin and solder joint due to CTE-mismatch of component and PCB

The stiffness of the pin can be approximated based on the Euler-Bernoulli beam theory. The pin is simplified to a beam with a fixed support on the solder side and a free end on the component side.

Due to its visco-plastic material behavior the solder joint stiffness cannot be represented by a simple linear-elastic model. In this work the material behavior was approximated with a linear-elastic and ideal plastic material model. When analyzing the resulting stresses and strains in the solder joint one realizes the plastic deformation will mostly occur in bending mode with tensile strains perpendicular to the PCB as indicated in Fig. 4.

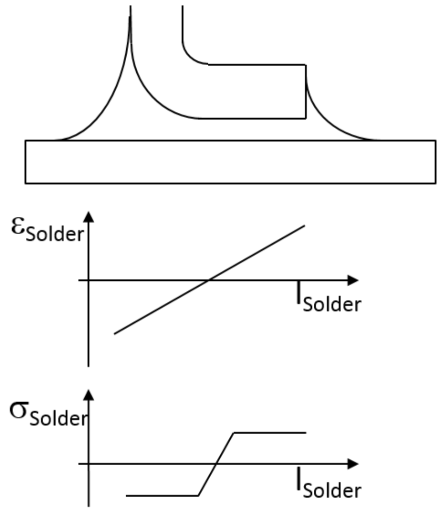


Figure 4 – Schematic tensile deformation in a gull wing lead solder joint and stress distribution at the end of a temperature dwell

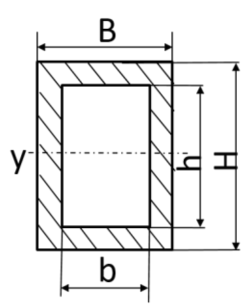
With the ideal-plastic material model for the solder the load share between pin and solder joint can be calculated analytically. As a result the plastic strain in the solder joint is evaluated as damage parameter. Similar to FEM calculations the accumulated plastic strain in one thermal cycle can be used to compare different designs concerning lifetime under thermo-mechanical loading. The relation between accumulated plastic strain ε and number of cycles to failure N_f is based on the Coffin-Manson approach:

$$\frac{N_{f1}}{N_{f2}} = \left(\frac{\varepsilon_2}{\varepsilon_1}\right)^C$$

Typical values for the coefficient C found in literature range from 1 .. 2 [8]. For the following calculations an exponent of 1.4 is chosen.

Calculations for a 176 pin QFP package with a side length of 24 mm and Copper pins of 0.2*0.22 mm² cross section area reveal that at least 25% of the total deformation induced by a temperature cycle is covered by elastic bending of the pin. These calculations imply a solder joint formation similar to the schematic drawing at the bottom of Fig. 1. This load share decreases with any change in solder volume. On the one side for a decreasing solder volume the stiffness of the solder decreases leading to more deformation induced directly into the solder joint. On the other side an increase in solder volume will predominantly lead to increased wetting of the pin shaft. This will increase the stiffness of the pin shaft leading also to a higher part of the deformation induced into the solder joint.

Fig. 5 shows the basic formula describing the moment of inertia of the additional solder on the pin shaft. The thickness of this additional layer influences the stiffness in a cubic way. Therefore the excess solder can have a significant effect despite its low intrinsic stiffness.



$$W_y = \frac{BH^3 - bh^3}{6H}$$

Figure 5 – Moment of inertia of hollow profile [9]

Calculating the relative change in lifetime under thermo-mechanical loading conditions using the model described above requires a few additional simplifications. The solder fillet shape for example is assumed to be triangular in a cross section and the wetting of the pin shaft is approximated to have a constant thickness.The results for the 176 pin QFP package can be approximated with a polynomial function in a limited regime. This function is shown in Fig.6.

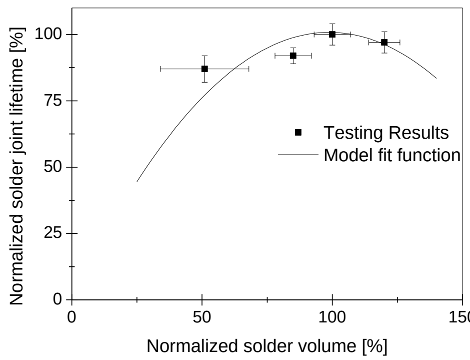


Figure 6 – Solder joint lifetime as a function of solder volume

The testing results plotted in Fig. 6 are derived for a QFP package in TCoB on 200 samples with temperature ranging from -40°C up to 125°C. The solder volume was modified by using different stencil thicknesses in the SMD assembly. 100% solder volume roughly represents a solder joint shape as plotted in Fig. 1 Class 3. The normalized lifetime plotted is based on the mean time to failure (MTTF). The Weibull distributions show a parallel shift of the diagram with variation of solder volume indicating the diagram in Fig.6 is also valid for other failure probabilities.

To calculate the solder joint shape a software for the modelling of liquid surfaces [10] was used. This finite element code models the solder joint shape in the equilibrium state based on surface tension and other energies. Fig. 7 shows the nominal solder joint shape for the four cases plotted above.

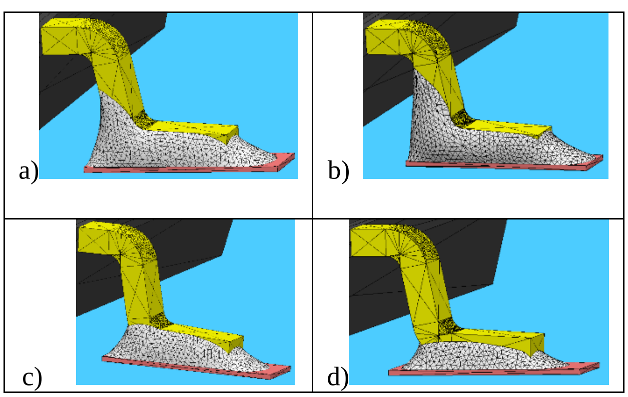


Figure 7 – Different solder joint shapes. a) 100% solder volume, b) 120% solder volume, c) 80% solder volume, d) 50% solder volume

Cross sections of failed solder joints from the TCoB test confirm the expected solder joint shape and failure mode. The joint seen in Fig. 8 represents an example for the model with 120% solder volume. The wetting of the pin shaft can clearly be seen although most of the excess solder is strongly deformed and cracked in the temperature cycling.

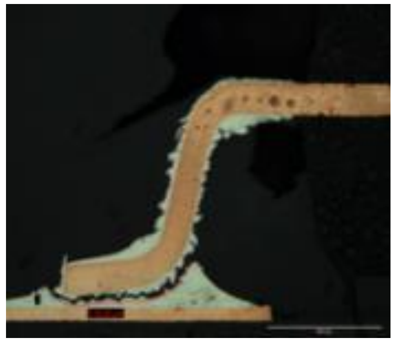


Figure 8 – Cross section image of a solder joint after TCoB testing.

Influence of solder volume on other failure modes

Besides temperature cycling there are other potentially critical loading conditions relevant in automotive applications. Most importantly vibration loads and electrochemical migration may lead to failures of the electronic control units. Packages with flat gull wing leads in general are relatively robust to vibrational loading due to the spring effect of the gull wing leads. The most common failure mode is cracking in the gull wing lead. [11] The solder volume has only limited effect on this type of failure. The influence on the eigenfrequency of the system is negligible. High solder volumes leading to wetting of the pin shaft may decrease the stress in the copper lead, but due to the low Young‘s modulus of solder as compared to copper the lifetime increase will be relatively low. Additionally most failures in the gull wing are more likely to occur at locations next to the package body than close to the solder joint. [12]

Electrochemical migration on printed circuit assemblies can occur for specific combinations of humidity, temperature, ionic contamination and migration paths. Concerning solder volume for gull wing solder joints the only affected variables are distance of two neighboring solder joints and amount of flux residues. Both parameters become less critical with decreasing the solder volume. [13]

In addition to solder joint reliability the second important aspect concerning joint design is the processability. A failure mechanism affected by solder volume is bridging between two neighboring solder joints. To reduce this type of failure in mass production a reduction of solder volume is beneficial as well.

Conclusion

Several investigations in combination with different modeling approaches have shown that for gull wing solder joints there exists an optimal solder volume ensuring optimal product reliability in combination with cost-efficient processability. It is shown that an increase of solder volume beyond this optimum will lead to a reduction of solder joint lifetime in thermo-mechanical loading conditions.

The IPC standards J-STD-001F and A-610F require a minimum heel fillet height of solder thickness plus lead thickness for acceptance Class 3 and partially Class 2. This requirement is close to the optimal solder volume. To ensure compliance with this criterion taking into account the normal process scatter the nominal solder volume has to be significantly increased above this optimum. In the automotive industry process limits are often defined based on “six-sigma” bounds. This requires limits for a typical stencil printing process of up to +/- 50% of the nominal solder volume. [14] Therefore the assurance of Class 2 and Class 3 quality for solder joints of gull wing leads actually requires a nominal solder volume significantly above the optimal solder volume. Thereby an optimal design concerning product reliability is prevented.

These findings lead to the proposal of changing the criterion for Class 2 and Class 3 solder joint quality. A minimum heel fillet height of solder thickness plus 0.5*lead thickness is seen as sufficient for many requirements and allows for an optimal solder volume in the nominal design.

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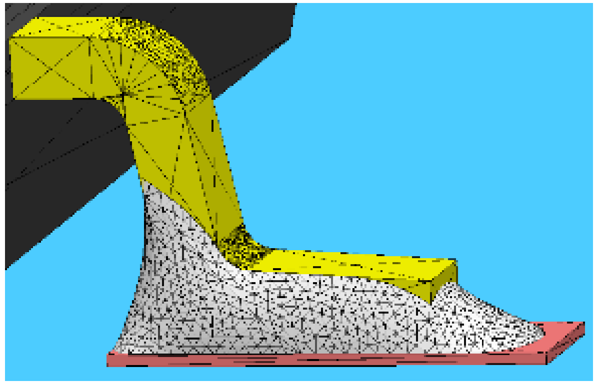
Topic and Agenda

Finding the optimal solder volume to optimize solder joint reliability of components with flat gull wing leads

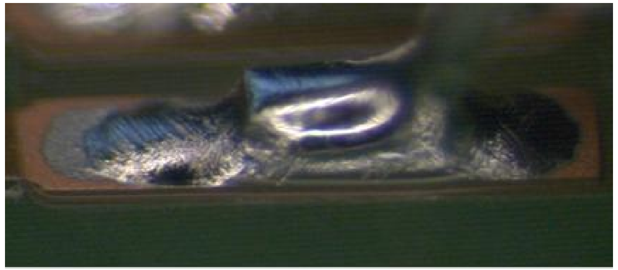


Agenda:

1. Introduction
2. Standards
3. Modelling solder joint lifetime
4. Optimal solder volume

Packages with flat gull wing leads

- Advantages:
  - High reliability
  - Relatively low cost



- Increasing requirements concerning temperature cycling:
  - Mounting of the ECUs in harsher environment locations
  - Increased power loss in ECUs as a result of major trends including miniaturization and electrification

Geometry requirements: IPC A-610F

8.3.5.6 Flat Gull Wing Leads – Minimum Heel Fillet Height (F)

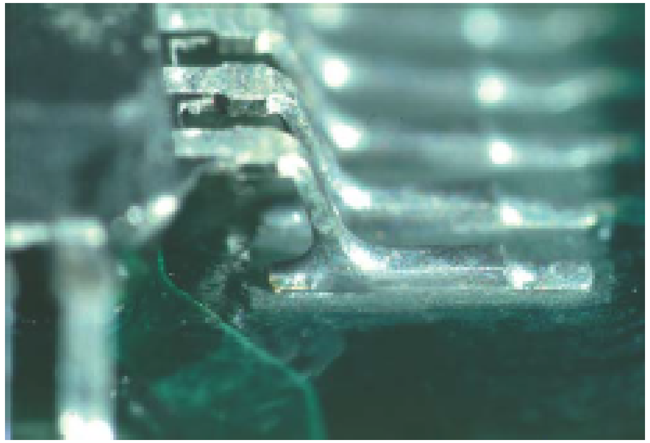


Figure 8-100

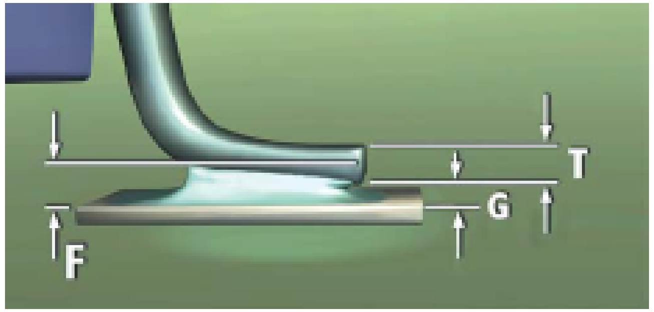


Figure 8-101

Target – Class 1,2,3

- Heel fillet height (F) is greater than solder thickness (G) plus lead thickness (T) but does not extend into knee bend radius.

Acceptable – Class 1

- A wetted fillet is evident.

Acceptable – Class 2

- Where lead thickness (T) is equal to or less than 0.4 mm [0.015 in], the minimum heel fillet is solder thickness (G) + lead thickness (T).
- Where lead thickness (T) is greater 0.4 mm [0.015 in], the minimum heel fillet is solder thickness (G) + 50% lead thickness (T).

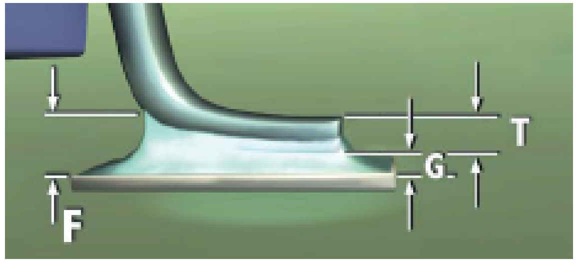


Figure 8-102

Acceptable – Class 3

- Minimum heel fillet height (F) is equal to solder thickness (G) plus lead thickness (T) at connection side.

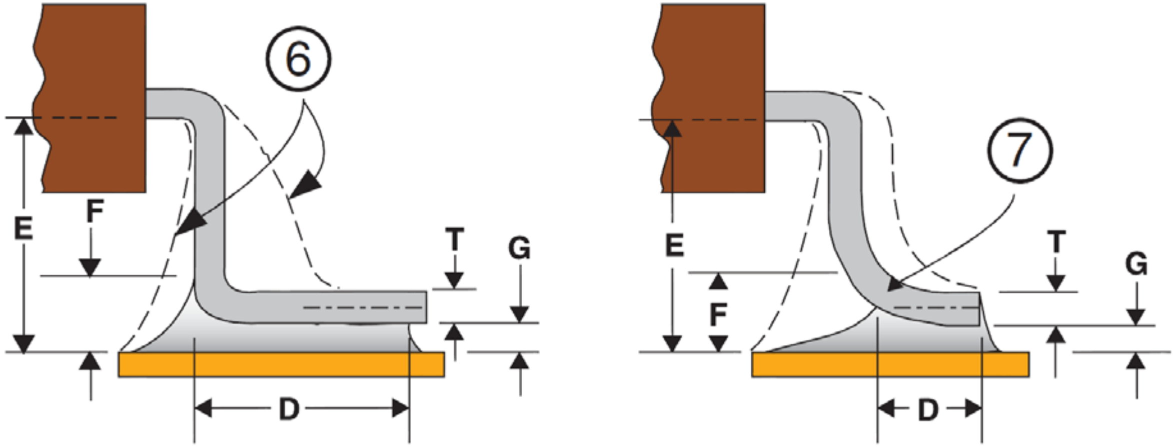
Acceptable – Class 1,2,3

- In the case of a toe-down configuration, see Figure 8-103, the minimum heel fillet height (F) extends at least to the mid-point of the outside lead bend.

Excerpt from: *"IPC-A-610F: Acceptability of Electronic Assemblies"* ©

Geometry requirements: IPC J-STD-001F

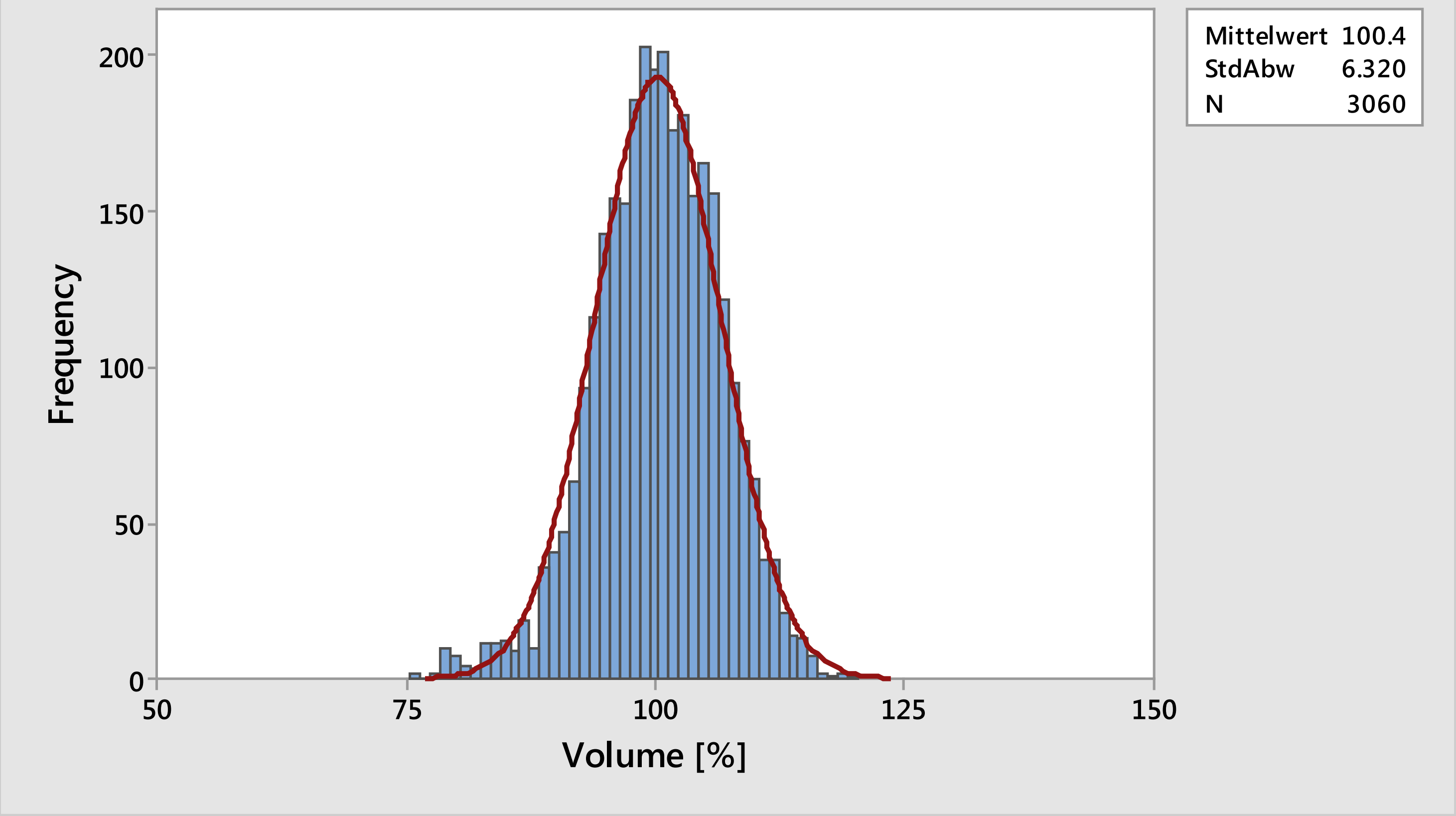
Feature		Class 1	Class 2	Class 3
Minimum Heel Fillet Height (Dimension F)	(T) ≤ 0.4 mm [0.015 in]	Wetting is evident	(G) + (T)	(G) + (T)
	(T) > 0.4 mm [0.015 in]		(G) + 50% (T)	



Excerpt from: „*IPC J-STD-001F: Requirements for Soldered Electrical and Electronic Assemblies*" ©

Ensuring IPC class 3 with 6-sigma process (1)

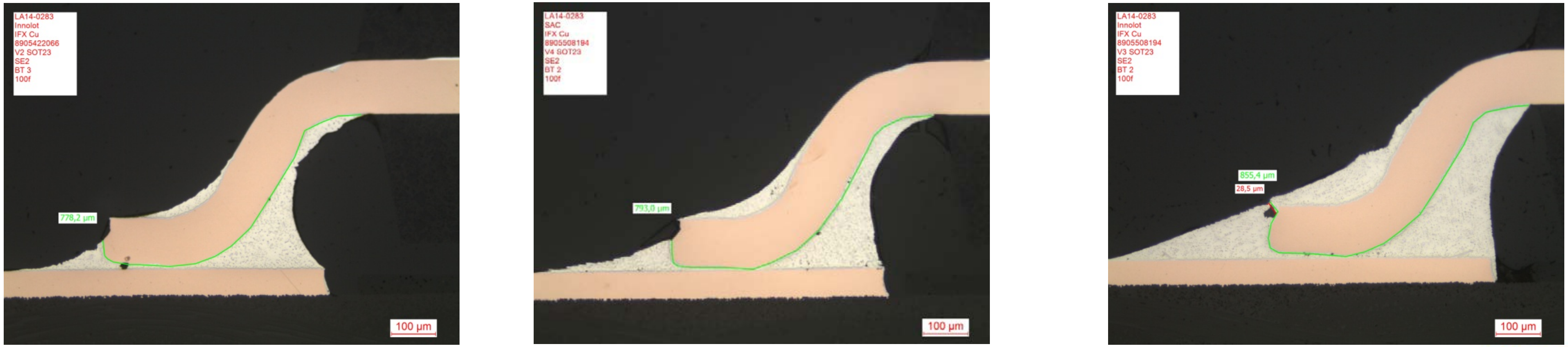
- Typical solder printing process involves scatter of volume



Example for distribution of printed solder volume

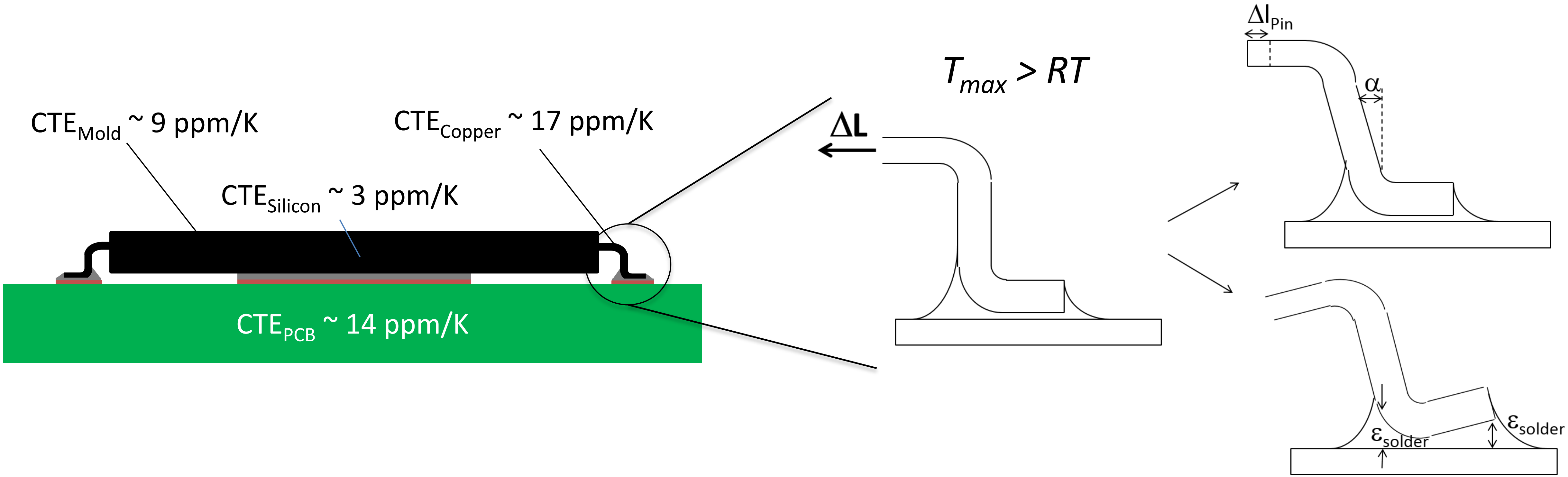
Ensuring IPC class 3 with 6-sigma process (2)

- High nominal solder volume required to ensure 6-sigma process
- The tolerances of the solder paste printing process cause a scatter of reflowed solder thicknesses around the pin



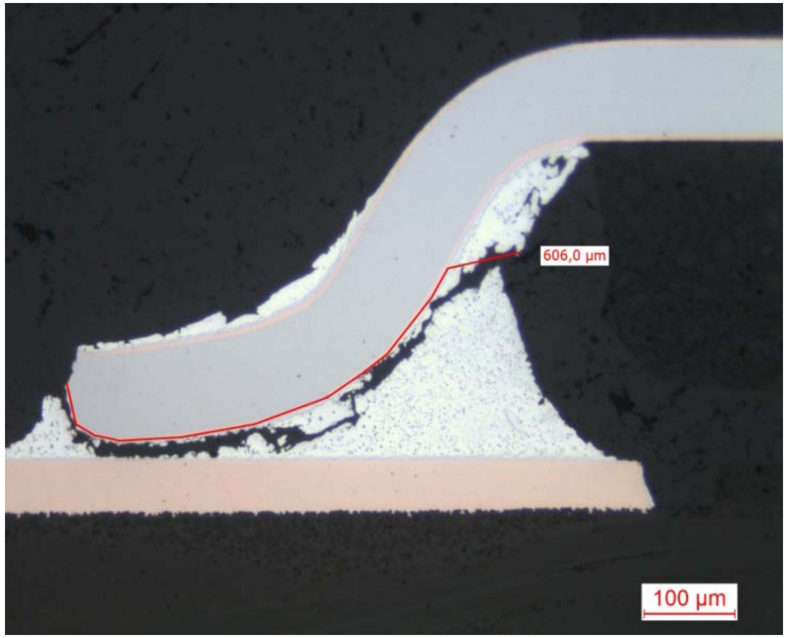
SOT23 pins with different amounts of solder volume

Solder joint fatigue in temperature cycling (1)

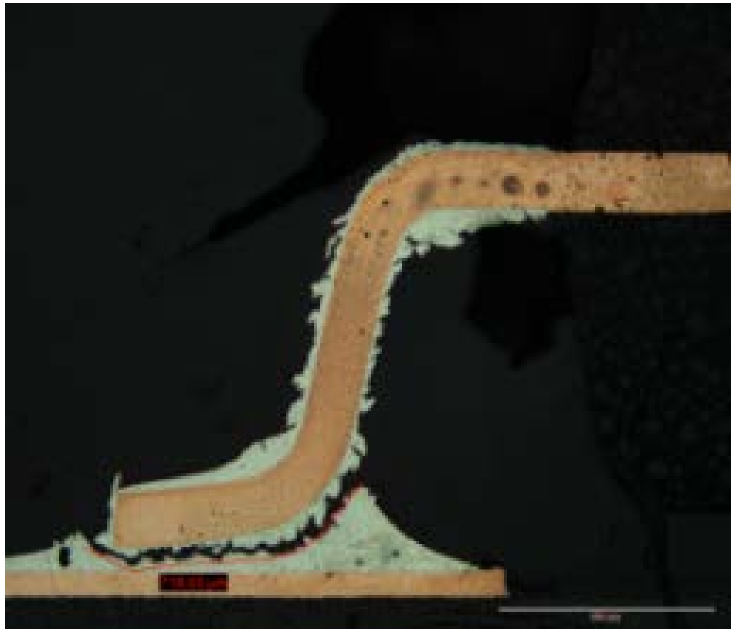


Solder joint fatigue in temperature cycling (2)

- Thermo-mechanical fatigue typically leads to grain boundary cracking in solder joints



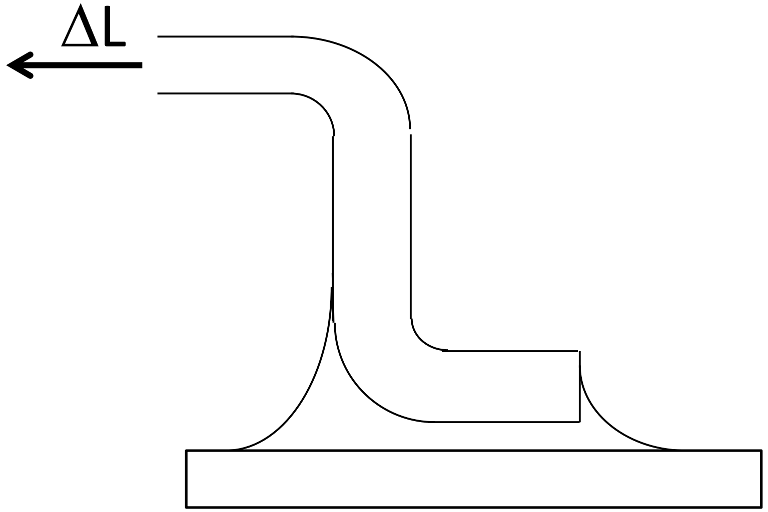
SOT23

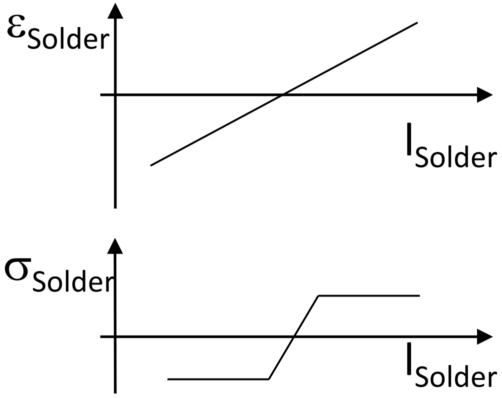


LQFP176

Modelling solder joint lifetime (1)

- Damage parameter: accumulated plastic strain in one thermal cycle
- Solder modelled with linear-elastic / ideal plastic behavior for simplification
- Analytical model derived to describe the effect of solder volume





Modelling solder joint lifetime (2)

- Correlation of plastic strain with solder joint lifetime with Coffin-Manson approach:

$$\frac{N_{f1}}{N_{f2}} = \left(\frac{\varepsilon_2}{\varepsilon_1}\right)^C$$

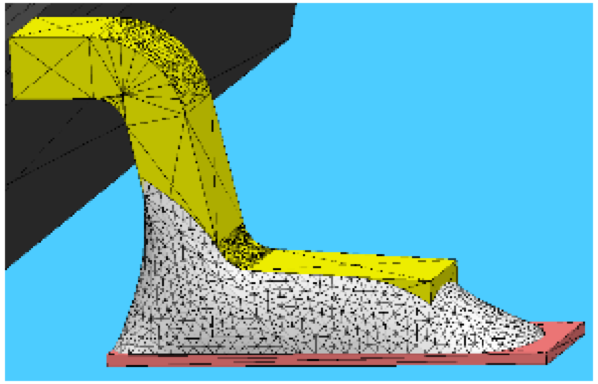
N_{f1} .. Lifetime of joint 1
N_{f2} .. Lifetime of joint 2
ε_{f1} .. Plastic strain in joint 1
ε_{f1} .. Plastic strain in joint 2

- Exponent *C* found in literature for lead free solder typically in range 1 .. 2

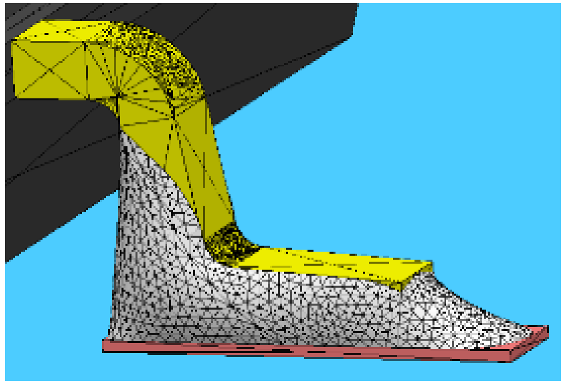
→ *C* = 1,4 chosen for current investigation

Effect of high solder volume (1)

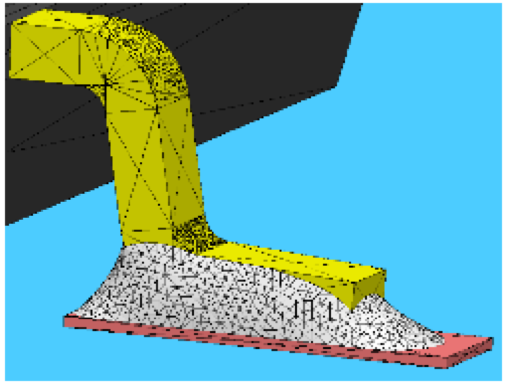
- Increasing solder volume leads to wetting of the pin shaft



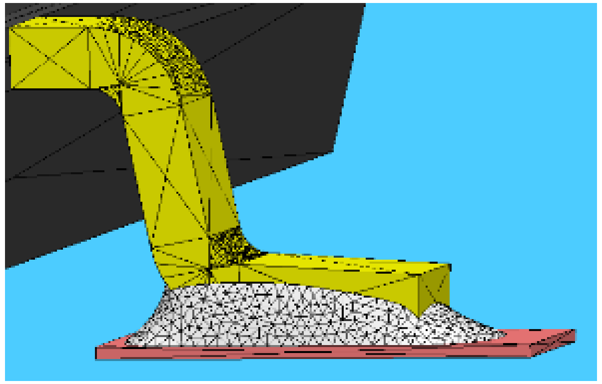
a) Reference solder joint (100% solder volume)



b) 120% solder volume

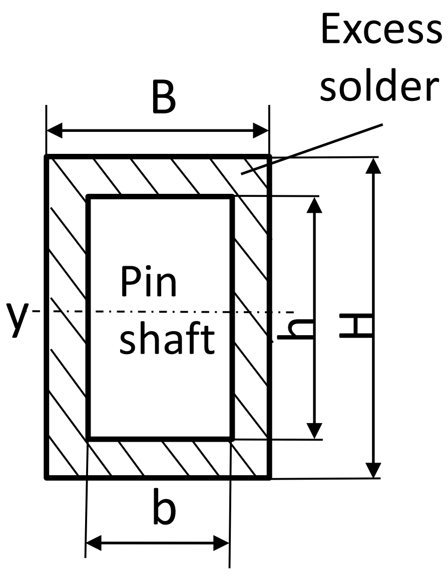


c) 80% solder volume

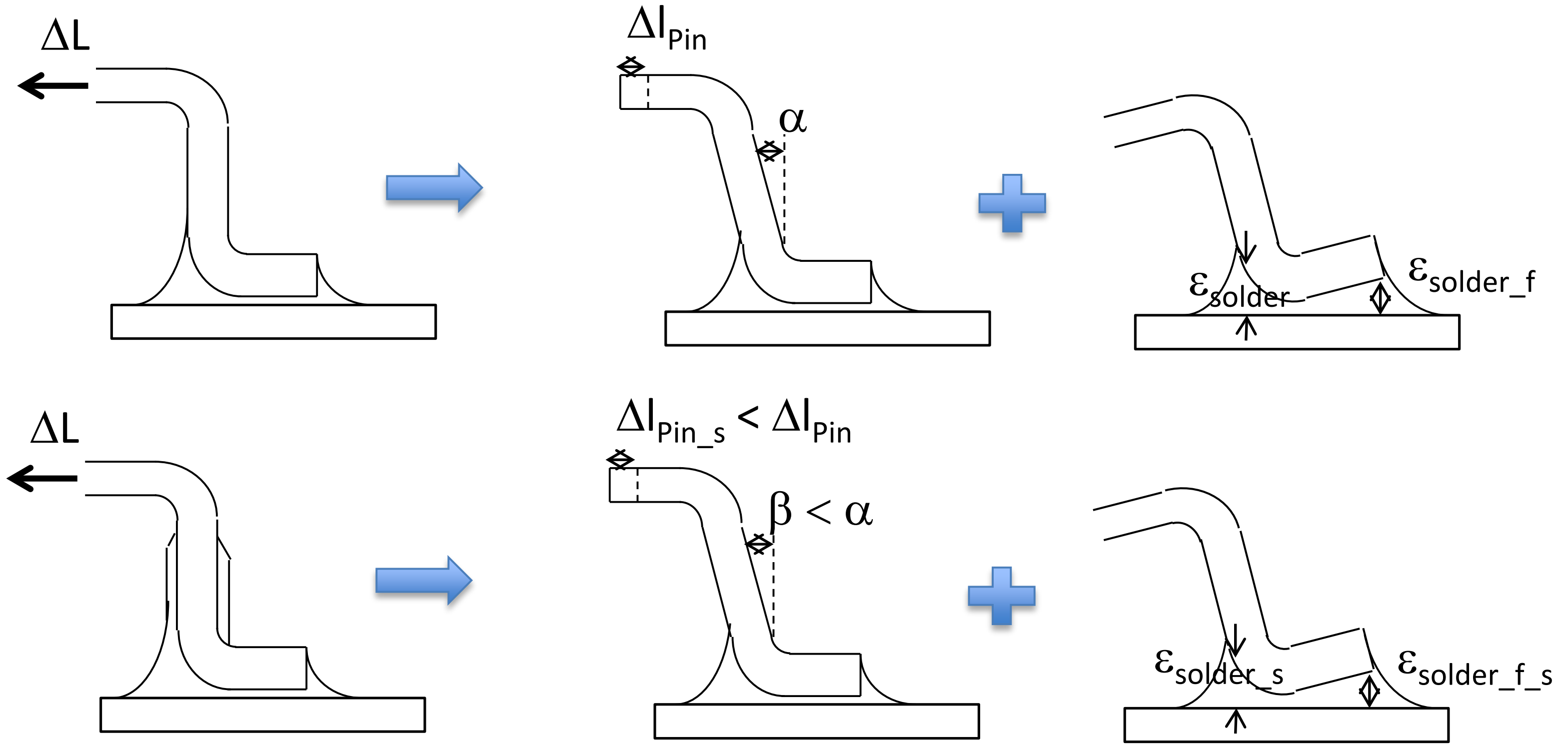


c) 50% solder volume

Effect of high solder volume (2)



$$W_y = \frac{BH^3 - bh^3}{6H}$$

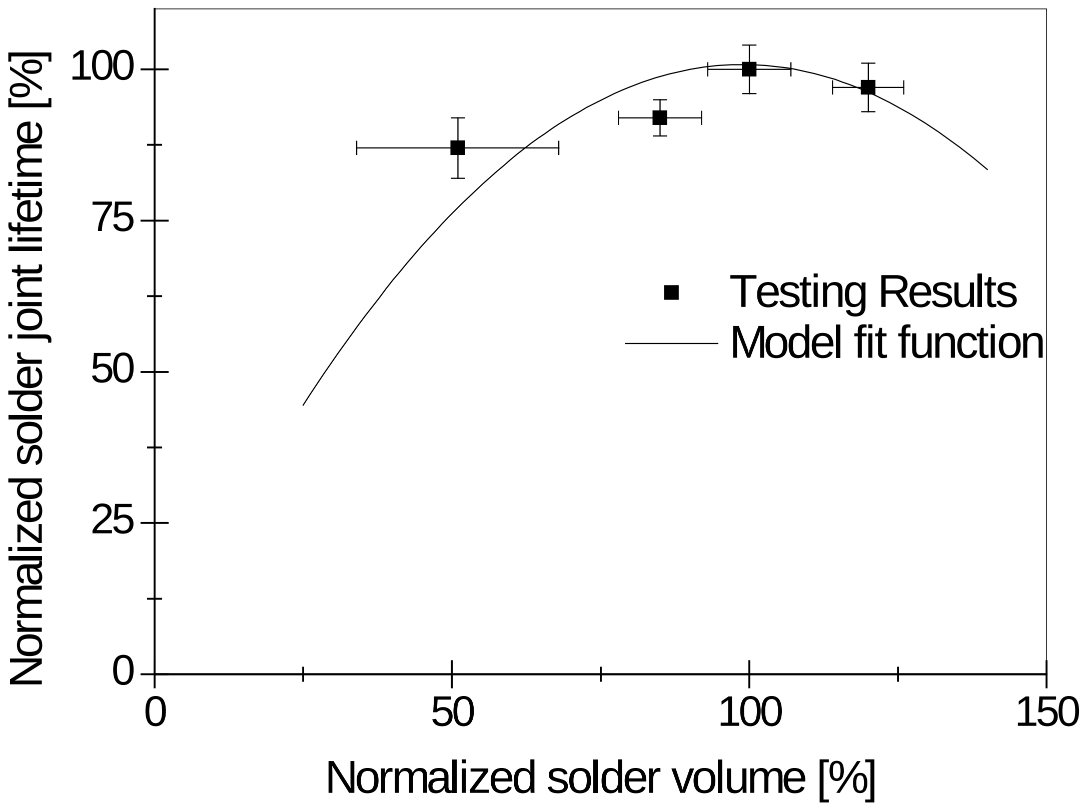


- Stiffening effect on pin shaft results in higher strain in solder

$$\varepsilon_{solder\_s} > \varepsilon_{solder}$$

ε_{solder_s} .. Plastic strain with excess solder
ε_{solder} .. Plastic strain in nominal case

Correlation of solder volume with solder joint lifetime



- Polynomial function fitted to model results described above
- Test results:
  - 176-pin QFP package
  - TCoB -40°C/125°C
  - MTTF plotted

Influence of solder volume on other failure modes (1)

Dynamic mechanical loading (e.g. vibration):

- ➢Packages with gull wing leads relatively robust
- ➢Most common failure mode is cracking of gull wing lead close to component
- ➢Influence of solder volume on PCB eigenfrequency negligible

→ **Very low influence of solder volume on lifetime in vibration loading**

Influence of solder volume on other failure modes (2)

Electrochemical migration

- ➢Distance between solder joints slightly increased with decreasing solder volume
- ➢Amount of flux residues in between solder joints reduced with decreasing solder volume

→ Risk for electrochemical migration reduced with decreasing solder volume [1]

[1] P.-E. Tegehall: "Impact of Humidity and Contamination on Surface Insulation Resistance and Electrochemical Migration", The ELFNET Book on Failure Mechanisms, Testing Methods, and Quality Issues of Lead-Free Solder Interconnects, pp 227-253, Springer, 2011

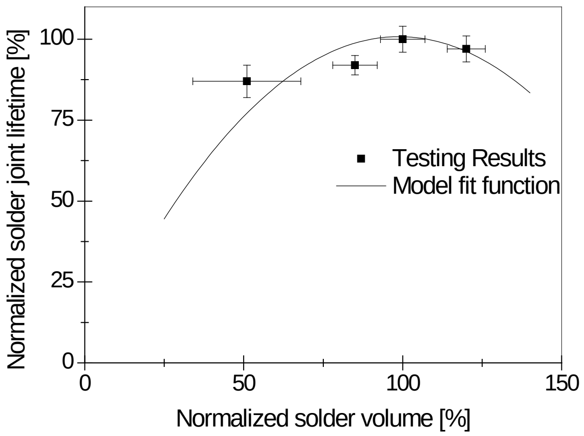
Influence of solder volume on other failure modes (3)

- Manufacturing process:
  - ➢Risk for solder bridging reduced with decreasing solder volume

→ **Moderate decrease of solder volume beneficial for process FOR**

Summary

- Concerning thermo-mechanical solder joint reliability there exists an optimal solder volume
- Increasing solder volume beyond this maximum has negative influence on various aspects in processability and reliability
- J-STD-001F and A-610F Class 3 requirement for minimum heel fillet height is close to optimal volume



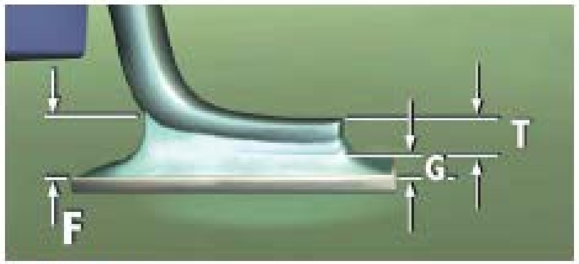


Figure 8-102

Conclusion

- Proposal to J-STD-001F and A-610F: Reduce requirement for minimum heel fillet height.

Current standard:

Feature		Class 1	Class 2	Class 3
Minimum Heel Fillet Height (Dimension F)	(T) ≤ 0.4 mm [0.015 in]	Wetting is evident	(G) + (T)	(G) + (T)
	(T) > 0.4 mm [0.015 in]		(G) + 50% (T)	

Proposal:

Feature		Class 1	Class 2	Class 3
Minimum Heel Fillet Height (Dimension F)	all	Wetting is evident	(G) + 50% (T)	

Thank you!

Questions?