Effect of Soldering Method, Temperature, and Humidity on Whisker Growth in the Presence of Flux Residues

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Abstract
Since the electronics industry moved to lead-free solders that typically have a tin content of more than 95% there has been concern about the possibility of circuit malfunctions due to whisker growth. It is now generally accepted that whisker growth is a response to compressive stress within the tin crystal and the challenge is to identify and eliminate or at least minimize the processes that can generate such stress. Corrosion has been identified as one source of that stress and in this paper the authors report a study directed at identifying the relationship between the extent of corrosion and the concomitant whisker growth. Printed circuit coupons with an OSP finish were soldered with SAC305 solder using wave, reflow, and hand soldering methods with flux formulations typical of current commercial practice. These coupons, soldered but without components, were exposed to three environments for up to 3000 hours: 40°C/95%RH, 60°C/90%RH and 85°C/85%RH. As well as recording the location of whiskers, their density, and length as a function of time, the extent of corrosion of the solder after 1000, 2000 and 3000 hours was measured by cross-sectioning. The ultimate determinant of whether or not whiskers appeared was the environment to which the test pieces were exposed. The highest incidence (whiskers per unit area), fastest growth rate, and greatest length occurred on test pieces exposed to 85°C/85% RH. Whiskers occurred later, at a lower incidence, and grew more slowly at 60°C/95% RH but even after 3000 hours no whiskers were detected on test pieces exposed to 40°C/95% RH. The incidence and growth rate of whiskers was found to vary with the soldering method and the type of flux. Whisker growth occurred earliest on the test pieces that had been wave soldered. Geometry was found to have an effect with the concavity created on the edges of traces by the etching process apparently acting to focus the compressive stress and accelerate whisker growth in that area. The authors relate these trends in whisker growth to observations of the concurrent corrosion of the solder which in turn is related to the type of flux used. A preliminary conclusion is that the likelihood of whisker growth occurring on lead-free assemblies soldered using no-clean technologies can be significantly reduced by using a flux which does not promote the sort of corrosion that can generate compressive stress in the solder.

Key Words: Whiskers, Corrosion, Lead-free Solder

Introduction
Although there are few confirmed reports of equipment failures due to whisker growth from solder joints rather than from electrodeposited tin finishes the possibility remains a concern for the electronics industry. It is now widely accepted that the primary driving force for whisker growth is relief of compressive stress and while it is well established that such stress can occur in electrodeposited coatings, particularly when the process is out of specification, a solder joint formed by unconstrained solidification from the molten state tends to be naturally stress-free. There are, however, ways in which compressive stress sufficient to induce whisker growth can be introduced to a solder joint. One such source of compressive stress recognized in tests such as JESD22A121, "Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes" is corrosion induced by exposure to heat and humidity.

The study reported in this paper investigated the relationship between whisker growth in conditions of heat and humidity and surface corrosion accelerated by the residues of the fluxes typically used in the three common soldering processes, wave soldering, hand soldering and reflow soldering.

Experimental Method
Alloy: Sn-3.0Ag-0.5Cu (SAC305), Sn-0.7Cu-0.06Ni-0.1Ge (SN100C®)
Test Vehicle: Interdigitated comb pattern, electrodeposited 35μm thick copper traces at 0.15 and 0.3mm spacing (Figure 1).
Soldering Methods: Solder was applied to the test vehicle by dip soldering, hand soldering and reflow soldering with a variety of commercially available wave soldering fluxes, flux cored solder wires and solder pastes using process parameters recommended for these materials (Table 1)

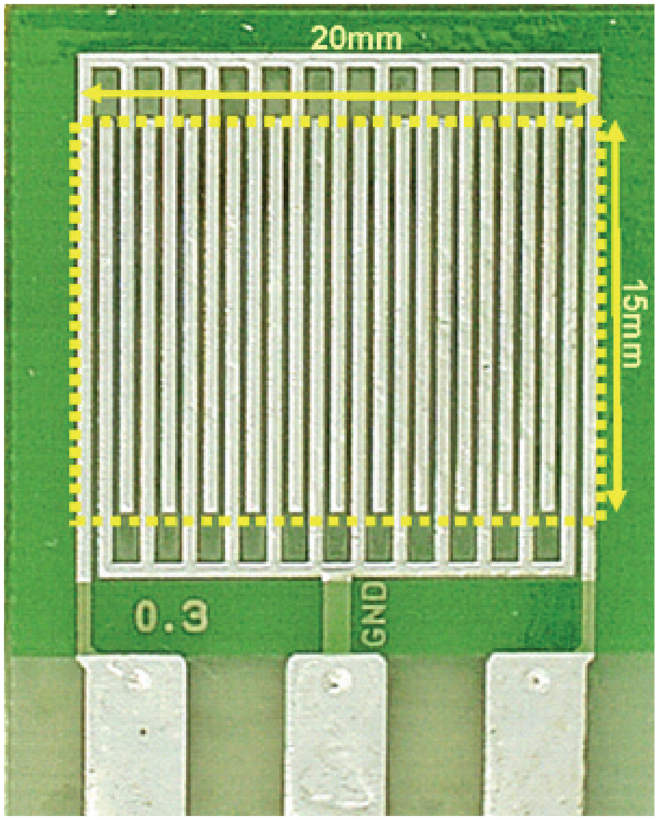

Figure 1. Test vehicle.

Exposure Environments: 40°C/95%RH
60°C/90%RH
85°C/85%RH

Inspection: Test vehicles were inspected for whiskers at up to 5000 hours.

Whisker Measurement: The area defined by the yellow dotted line in Figure 1 was inspected for whiskers. Whisker densities were determined by superimposing grids on SEM images of the traces and counting the squares in which whisker occurred. The longest whiskers in each field of view were noted and the length estimated in the SEM.

Corrosion Measurement: Figure 2 is typical of a cross-section of a soldered trace exposed to heat and humidity. Figure 3 is a magnified view of the edge of the trace where the solder is most exposed to flux residue and where most corrosion occurs. Solder corrosion was quantified by measuring on cross-sections such as this the total area of corrosion and expressing that as a percentage of the total cross-section area of the solder coating excluding the intermetallic compound at the solder/copper interface and in the matrix.

Table 1. Soldering Conditions

	Soldering Method		
	Hand	Dip	Reflow
Fluxes	A.B,C,D,E	F,G	H,K
Soldering Parameters	Tip 300°C Continuous	Solder 250°C	Ramp Profile 1.5°C/s 50s>227°C
A,B,C,D Halogenated Core Fluxes E: Halogen-free Core Flux F,G: Halogenated Liquid Fluxes H, K Halogenated Paste Medium			

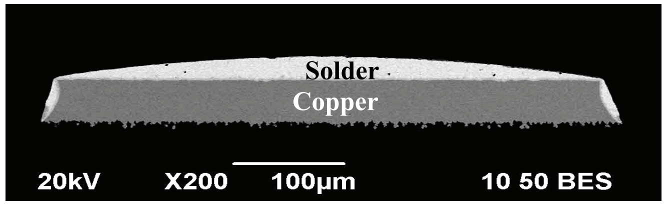

Figure 2. Cross-section of typical soldered trace

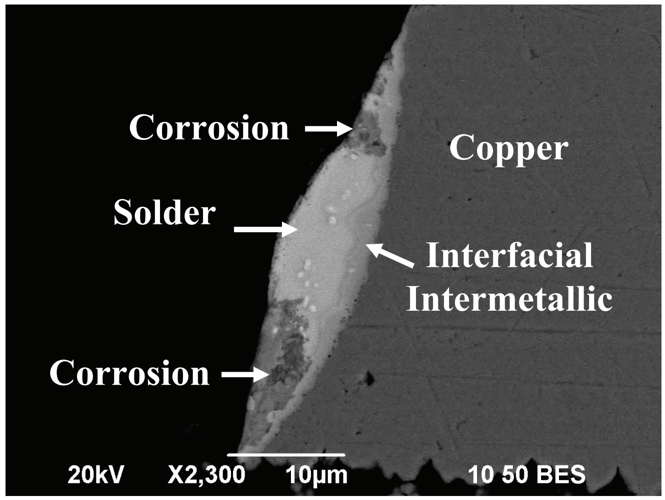

Figure 3. Cross-section of corroded solder

RESULTS

As expected the extent of corrosion increased with increasing temperature and humidity (Figure 4). Under the same environmental conditions the extent of corrosion varied with the soldering method with, on average, corrosion being greatest on the test vehicles that had been reflow soldered and least on those that had been hand soldered.

The typical distribution of whiskers is indicated schematically in Figure 5 with the greatest concentration of whiskers of the greatest length occurring on the edges.

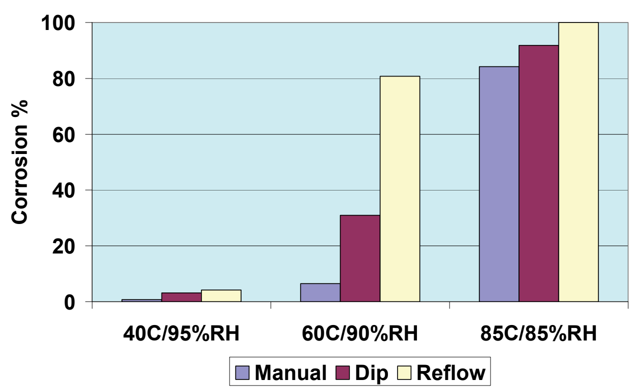

Figure 4. Corrosion at 3000h as a function of environment and soldering method.

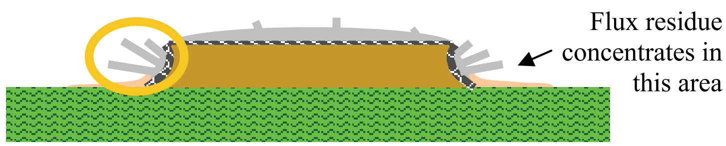

Figure 5. Schematic indication of pattern of whisker growth.

Significant whisker growth occurred only under the conditions of 60°C/90%RH and 85°C.85%RH and there is a relationship between the extent of corrosion and the maximum whisker length (Figure 6).

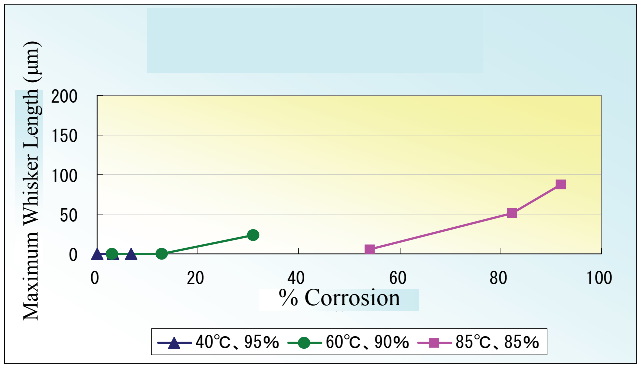

Figure 6. Maximum whisker length as a function of corrosion %

The environmental condition had a strong effect on the time to the occurrence of the first whisker (Table 2)

Table 2. Effect of environment on time to first whisker

Condition	Time	Acceleration Factor
40°C/95%RH	5000h	1
60°C/90%RH	1000-2000h	~3
85°C/85%RH	~500h	~10

The soldering method had a small but significant effect on the time to the occurrence of the first whisker (Table 3)

Table3. Effect of soldering method on time to first whisker

Method	Time	Acceleration Factor
Dip	500h	1
Hand	500-1000h	~x 1.5
Reflow	1000-2000h	~x 3

Maximum whisker length as a function of time in each of the three environments is reported on the basis of location in Figure 7. Maximum whisker length as a function of time at 85C.85%RH and location is reported on the basis of soldering method in Figure 8.

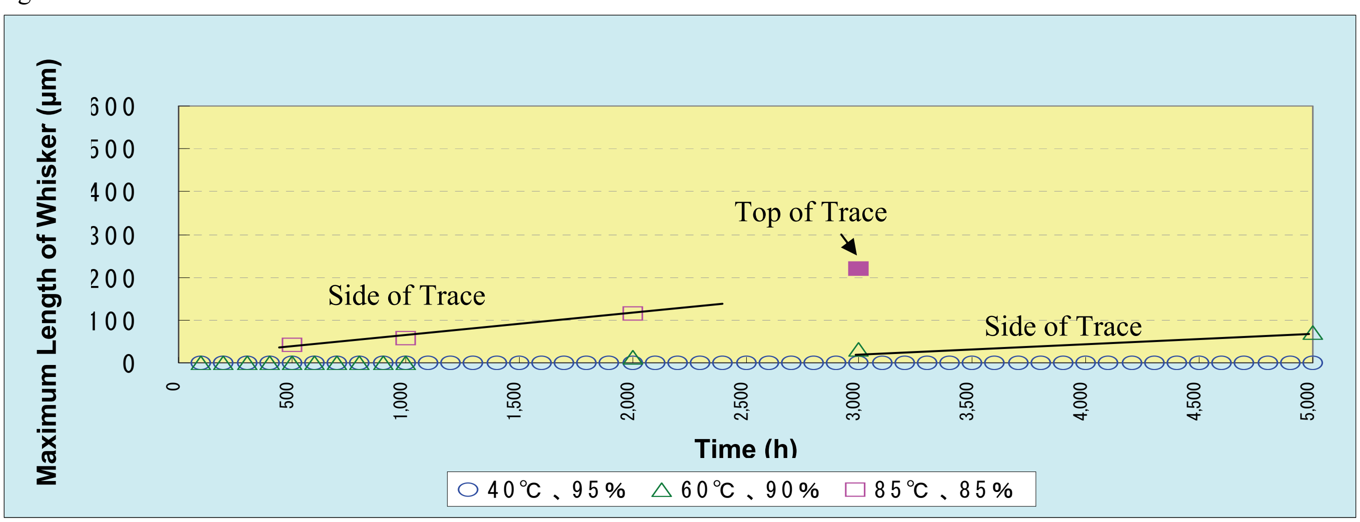

Figure 7. Maximum whisker length as a function of environment and time

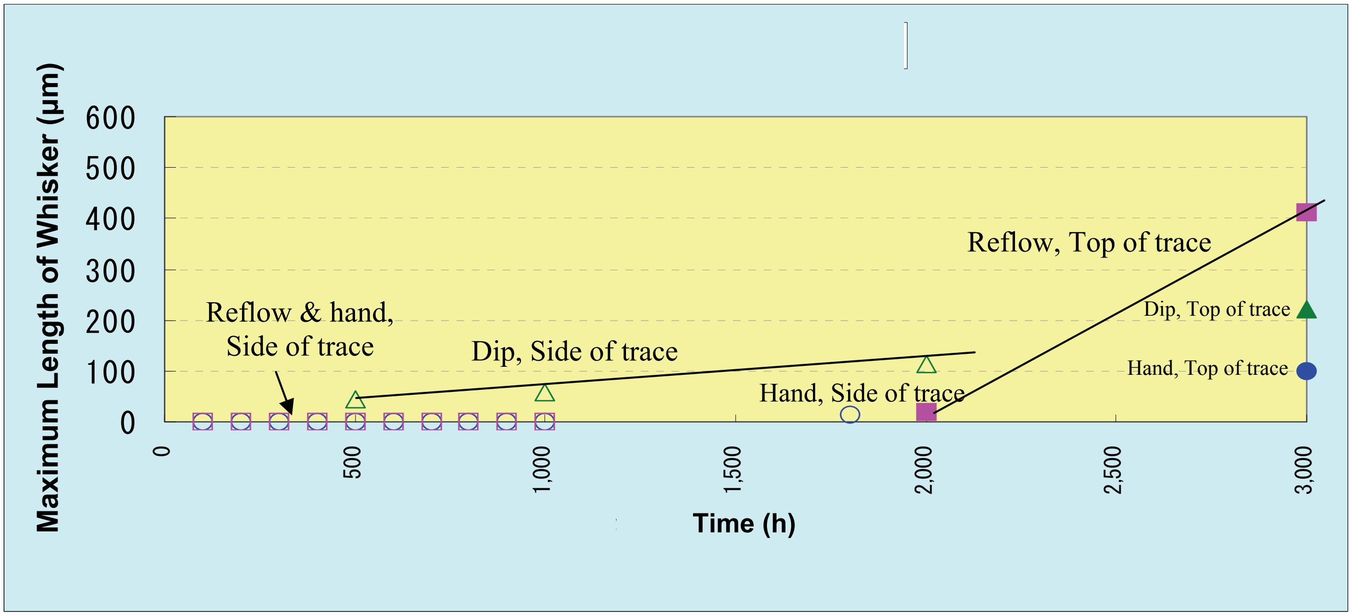

Figure 8. Maximum whisker length as a function of time at 85C/85%RH and soldering method

DISCUSSION

With no other obvious factors contributing to whisker grow the results confirm that corrosion induced by high temperature and humidity can induce of whisker growth. It can be hypothesised that the driver for the whisker growth is the compressive stresses generated by the increase in volume that occurs as the solder is converted to corrosion products.

It is generally considered that a whisker of 50µm represents a reliability risk since it has the potential to short typical circuitry. Under the conditions of this test whiskers of that length did develop in less than 1000h at 60°C/90%RH and 85°C/85%RH.

However, even at 95%RH a temperature of 40°C was not sufficient to generate whiskers of a length that could be considered a reliability risk.

The relationship between soldering method and whisker growth is presumably related to the extent to which the residue of the fluxing system used can contribute the ions that drive the corrosion process in the humid condition. There does not appear to be any obvious way in which the susceptibility of the solder itself could be affect by the method by which it is applied to the substrate as in all cases is solidifies unconstrained from the molten state.

The fact that most whisker growth occurs at the sides of the traces is presumably related to the fact that most of the flux residue ends up being concentrated in that area.

CONCLUSIONS

Under conditions of 60°C/90%RH and 85°C/85%RH corrosion that appears to be related to the character of the residues used in the soldering process can cause SAC305 solder to produce whiskers long enough to compromise circuit reliability. Where circuitry vulnerable to failure by shorts caused by whiskers is likely to be exposed to such conditions .consideration should be given to effective removal of flux residues or the selection of fluxes with residues that do not support the sort of corrosion that seems to drive whisker growth.

FUTURE WORK

Given the apparent relationship between flux residue and whisker growth under conditions of heat and humidity the possibility of formulating effective fluxes that have residues that do not promote whisker-inducing corrosion is being investigated.

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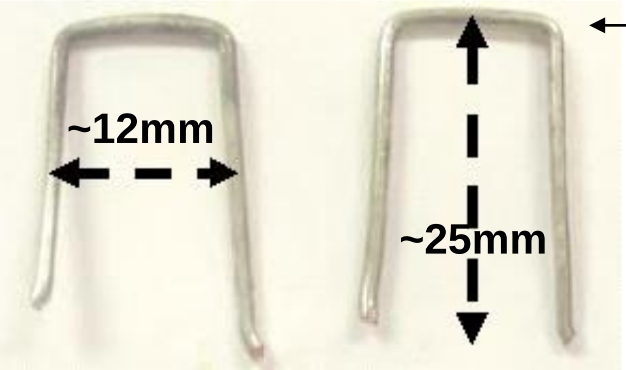
your partner for soldering solution

NIHON SUPERIOR

MOTIVATION

Testing by Trace Laboratories

Copper wire hot dip coated with the tested alloy was bent into U shape and tested according to:



Coating in Compression

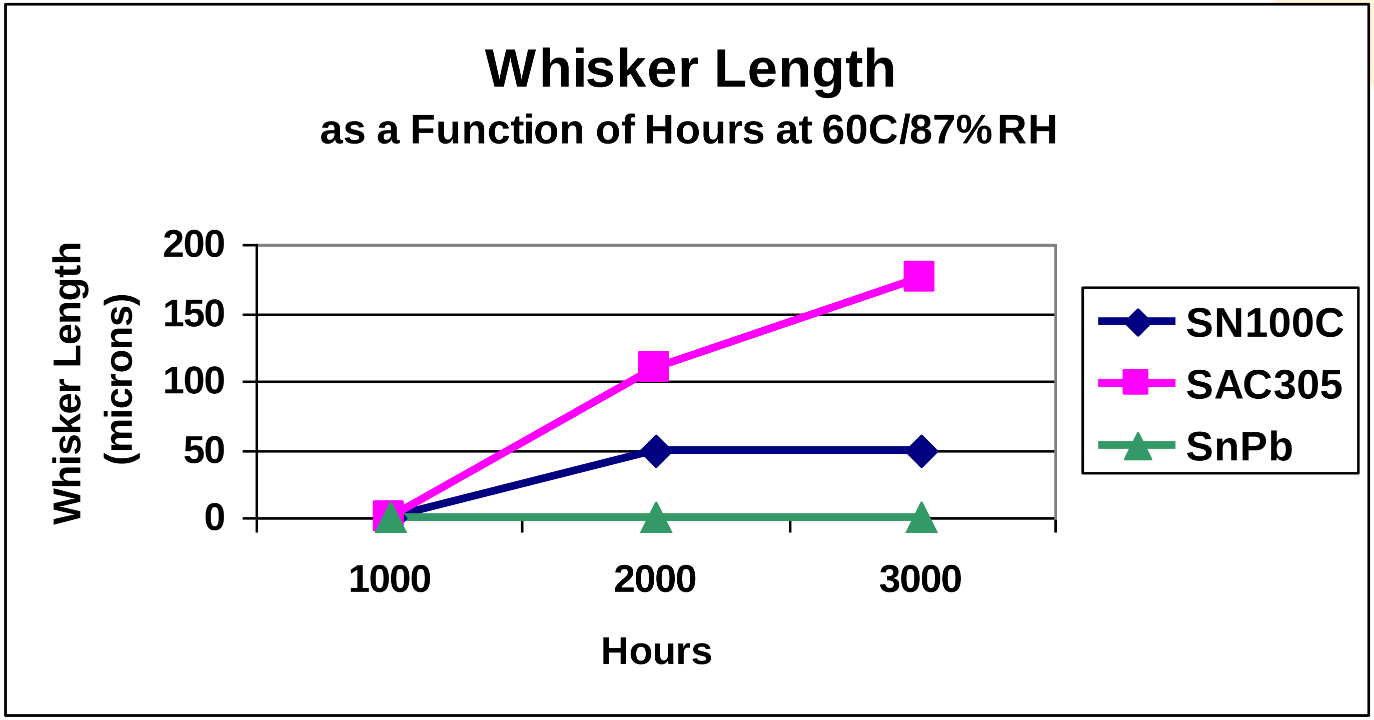
JESD22A121 –
"Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes"

SN100C

- **-40/+85° C 10**
  Inspect at 500 and 1000cycles → **No Whiskers!**
- **30° C/60% RH**
  Inspect at 1000, 2000, 3000 hours → **No Whiskers!**
- **60° C/87% RH**
  Inspect at 1000, 2000, 3000 hours

Some 50µm whiskers in area of compressive stress on bend

MOTIVATION (cont)



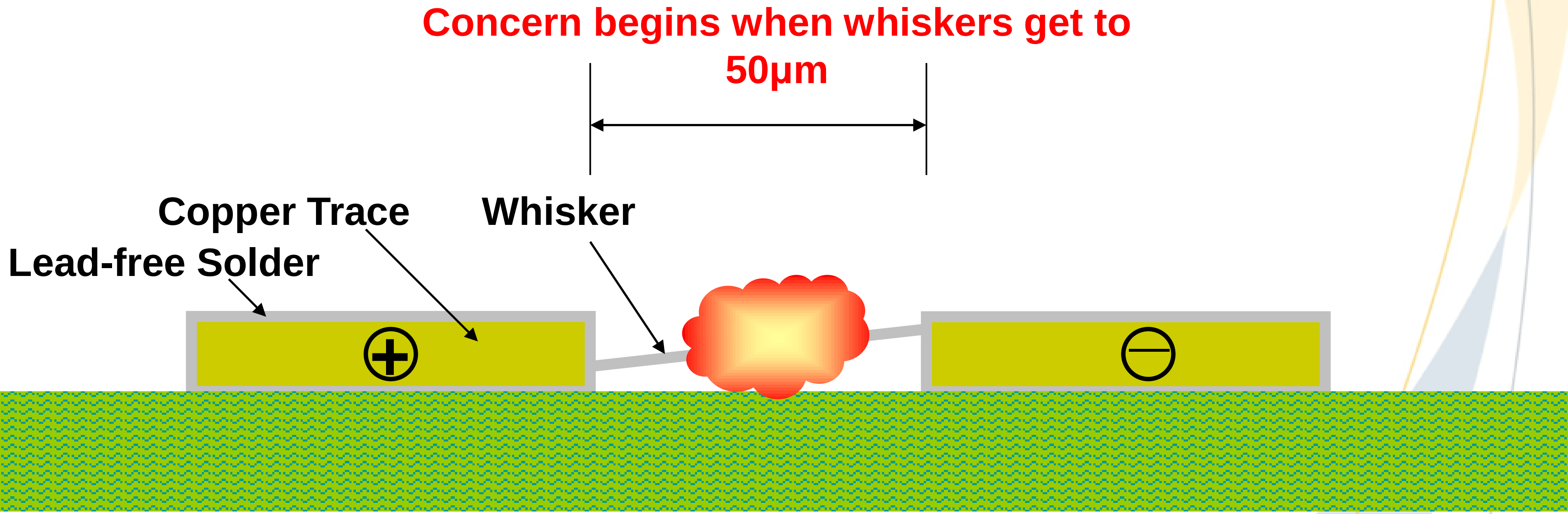
After an initial period of growth whiskers on SN100C do not grow further

Whiskers on SAC305 continue to grow…… probably driven by ongoing corrosion. SAC305 is more susceptible to corrosion

But then………..!!

WHY ARE WHISKERS A CONCERN?

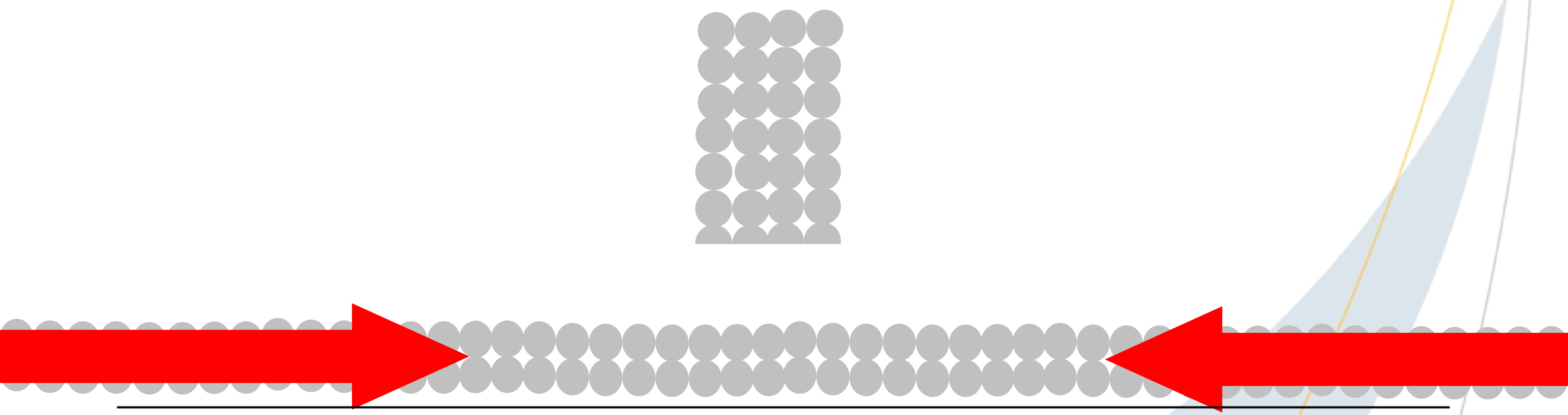
If a whisker bridges the gap between two conductors it can cause a short circuit that can carry enough current to stop the electronic circuit functioning correctly



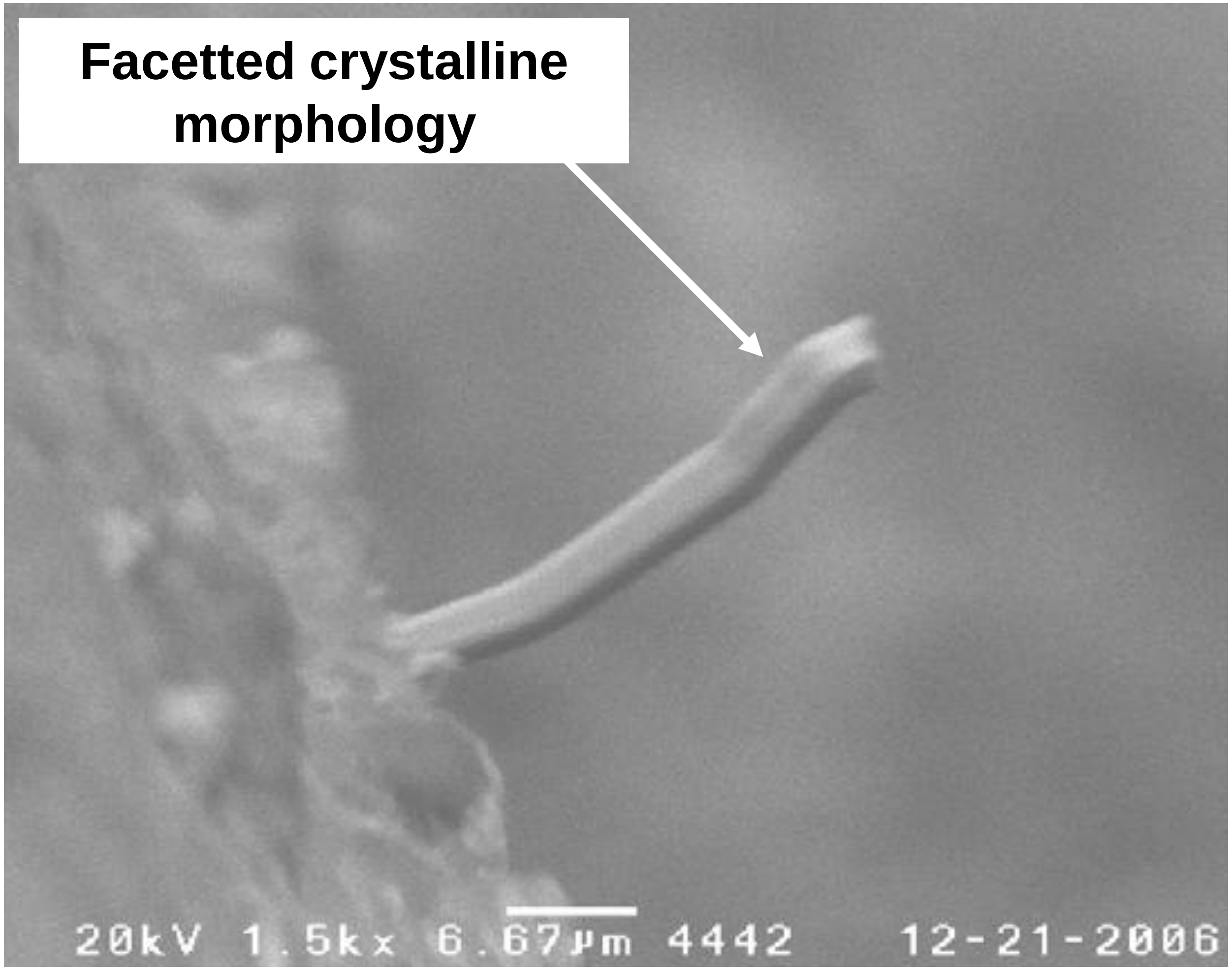
DRIVERS OF WHISKER GROWTH-1

Whiskers grow to relieve compressive stress in tin

Whiskers grow by atomic diffusion in a crystalline manner

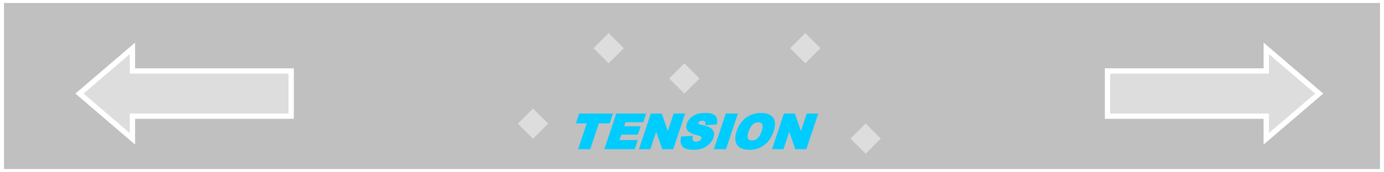


WHISKER-1

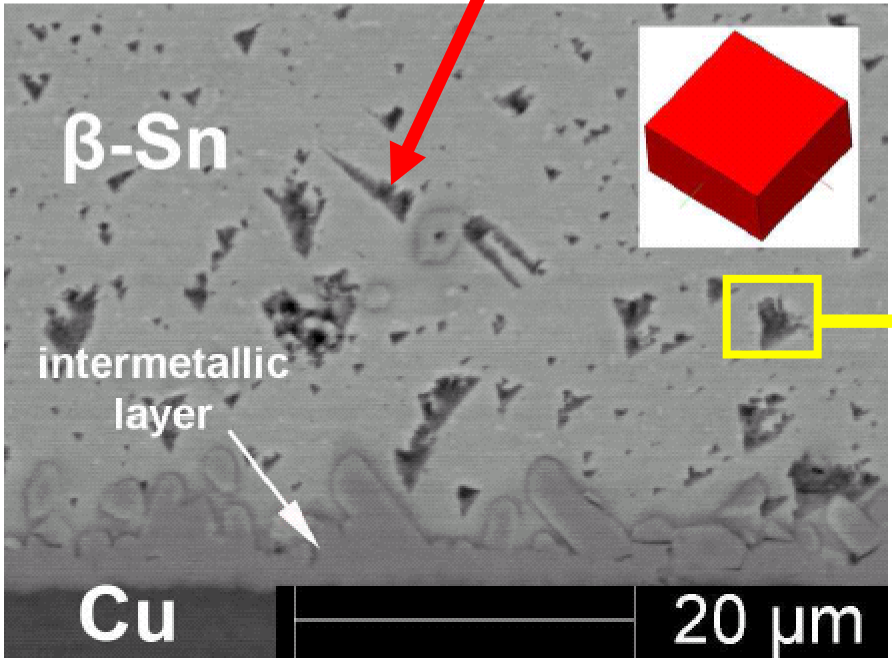

Facetted crystalline morphology
20kV 1.5kx 6.67µm 4442 12-21-2006

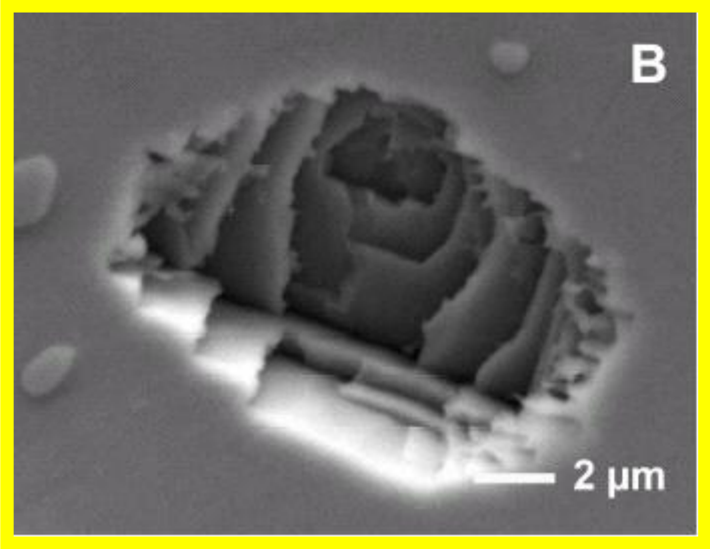
NEGATIVE WHISKERS?

What happens when the tin is under tensile stress?



Tension is relieved by formation of crystallographic voids



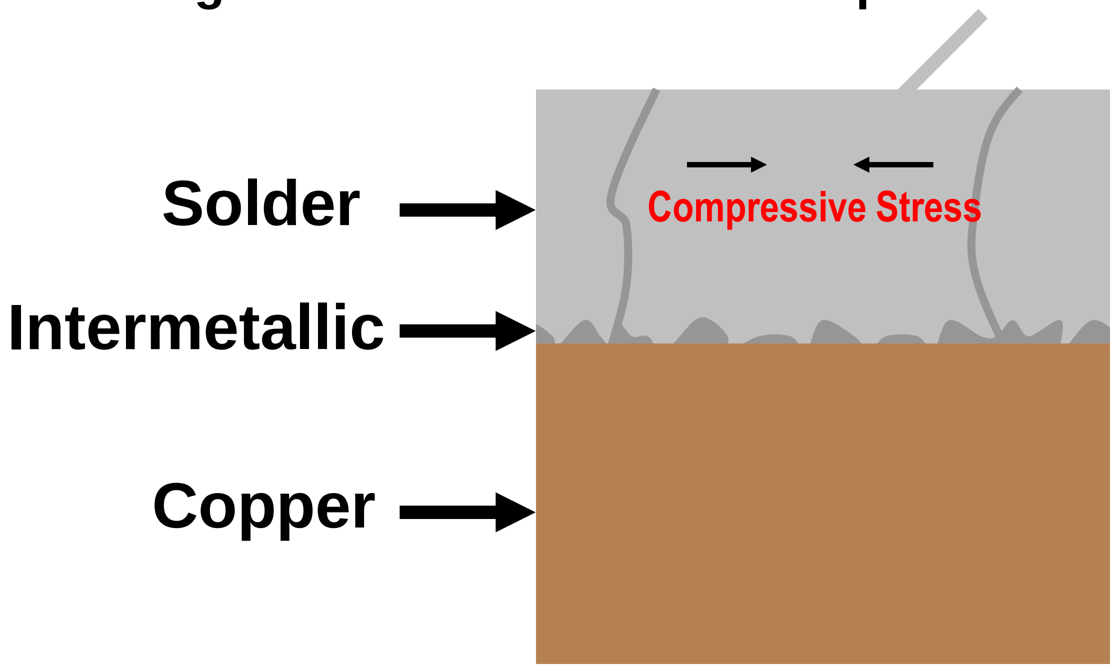


CRYSTALLOGRAPHICALLY-FACETTED VOID FORMATION IN THE MATRIX OF LEAD-FREE SOLDER JOINTS S. Belyakov, H V Atkinson and S P A Gill, Department of Engineering, University of Leicester. JEMS-1777

DRIVERS OF WHISKER GROWTH-3

Sources of Compressive Stress?

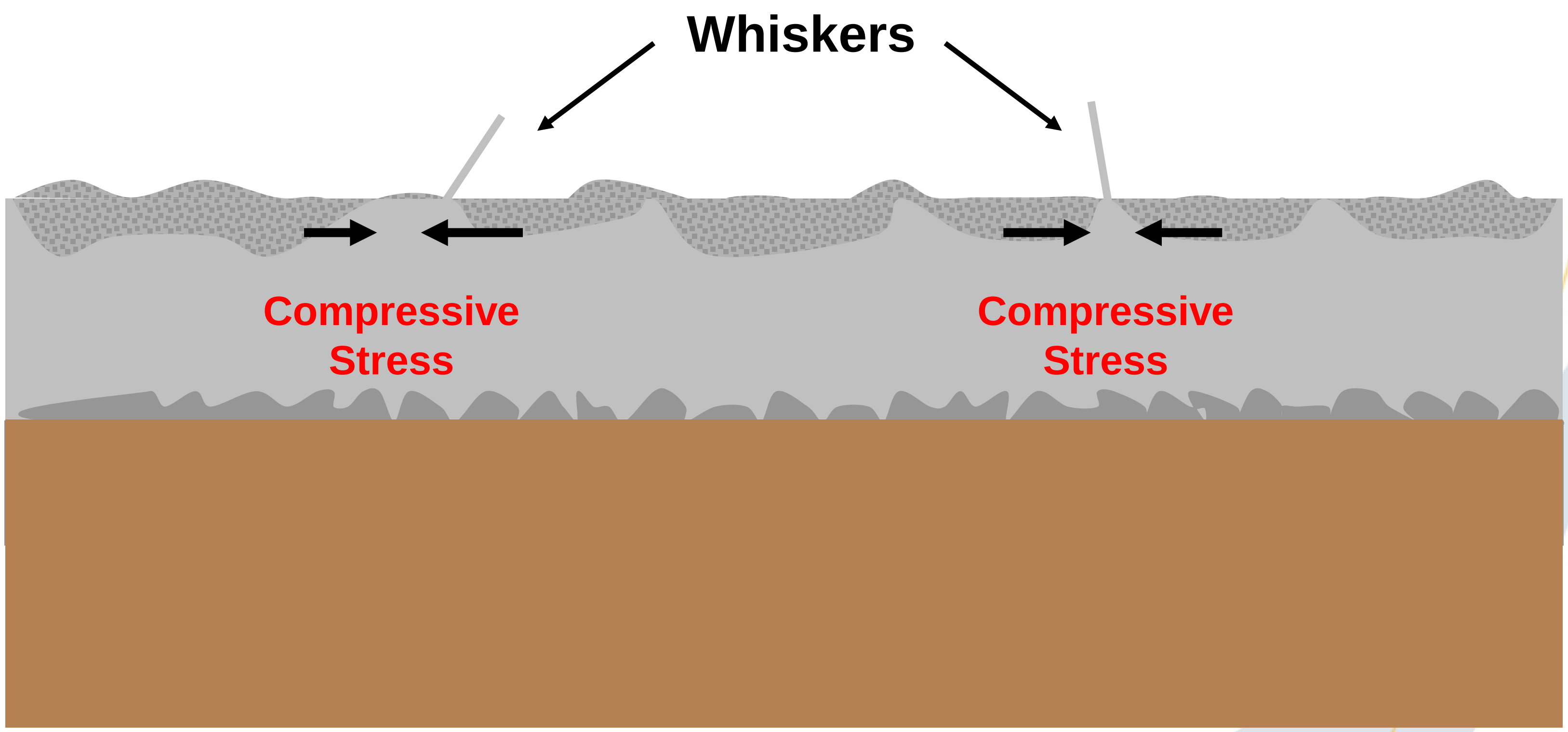
- As plated stress in electrodeposited coatings (especially bright plating)
- Strain induced by thermal cycling
- Externally applied stress (e.g. from press fit)
- Electromigration
- Columnar growth of intermetallic compound from solder substrate



DRIVERS OF WHISKER GROWTH-4

Corrosion

The focus of this study



WHISKER SUSCEPTIBILITY TESTS

JESD22A121 – Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes			
Condition	**Temperature**	**Humidity**	**Inspection**
Thermal Cycle	-40° C - +85° C 10 min dwell 10 min ramp	Ambient	500, 1000 cycles
Ambient	30° C	60% RH	1000, 2000, 3000h
Isothermal Heat and Humidity	60° C	87% RH	1000, 2000, 3000h

JEITA ET-7410 "Whisker Test Methods for Electrical and Electronic Equipment"			
Condition	**Temperature**	**Humidity**	**Inspection**
Ambient	30° C	60% RH	1000, 2000, 4000h
Isothermal Heat and Humidity	55° C	85% RH	2000h plus 4000h if whiskers still growing
Thermal Cycle	-40° C - +85° C 30 min dwell 30 s ramp	Ambient	1000 cycles extended to 2000 cycles If whiskers still growing

JEITA WHISKER GOAL

JEITA Technical Goal:

"Development of Whisker Suppression Technology"

Restrict whisker growth to
<50µm
during 1000 hours exposure to 85℃/85RH%.

Achievement of that goal was one of the motivating factors for the work reported in this presentation

OBJECTIVE OF THIS STUDY

- To look at the effect of process variables on the whisker growth on two of the most widely used Pb-free solders
- See if it is possible to meet the JEITA objective of no whiskers >50µm after 1000 hours storage in an environment of 85C/85%RH/

This Presentation

- **The experiment**
- **Measuring corrosion**
- **Relationship between corrosion and**
  - **The environment**
  - **Soldering method**
  - **Flux type**
- **Relationship between corrosion and whisker growth**
- **The next step?**

THE EXPERIMENT

Effect of

Soldering Method
- Dip
- Manual
- Reflow

Temperature & Humidity
- 40° C/95%RH
- 60° C/90%RH
- 85° C/85%RH

	Absolute Humidity
40° C/95%RH	1.0
60° C/90%RH	2.1
85° C/85%RH	6.4

on Whisker Growth

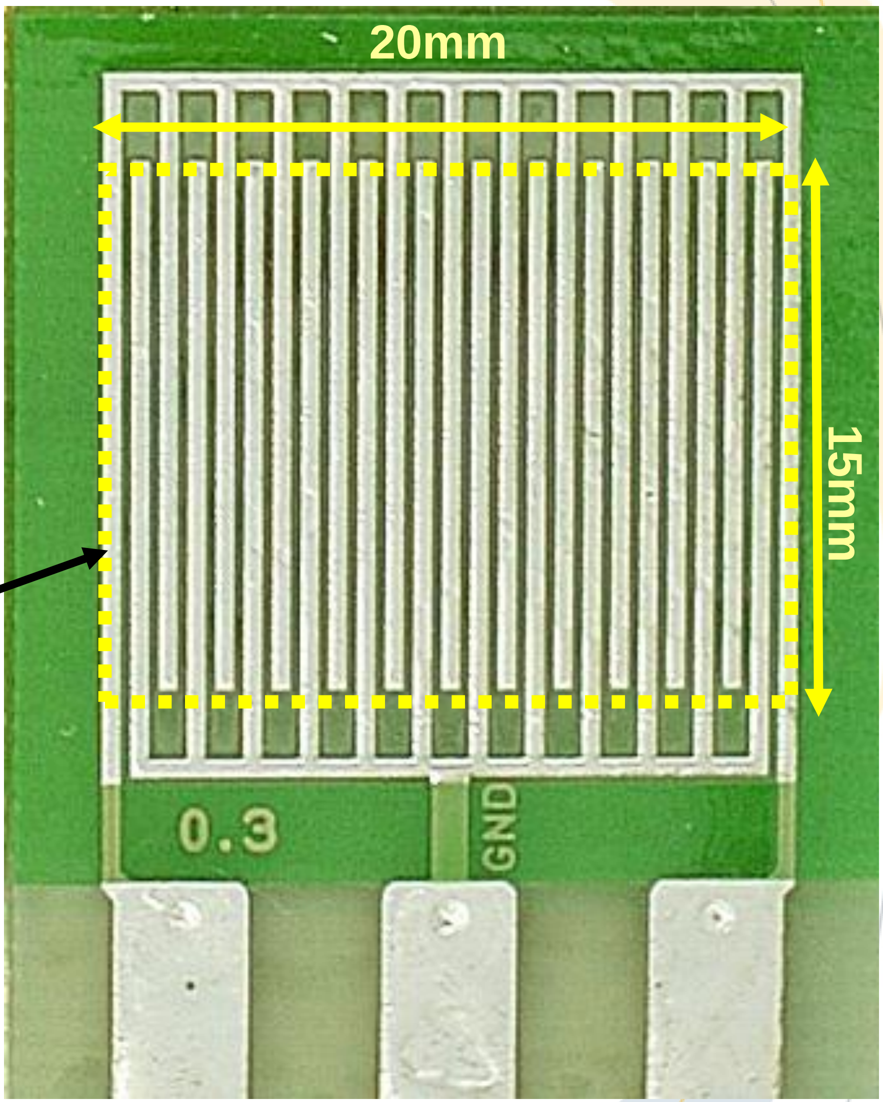
in the Presence of Flux Residues
- A wide range of commercial fluxes

TEST VEHICLE

Interdigitated Comb Pattern
Electrodeposited Copper Traces

Line Spacing	**0.3mm**
Cu Thickness	**35µm**
Traces	**25**

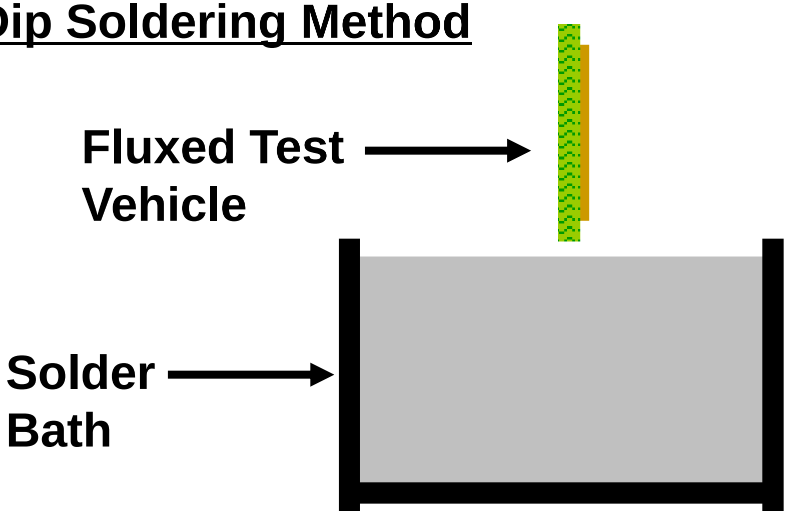
Inspection Area



SOLDERING METHODS

		Soldering Method		
		Manual	**Dip**	**Reflow**
Fluxes	**SN100C**	A, B, C, D, E	F,G	H
	SAC305	A, B, C, I, J	F, G	H, K
Soldering Parameters		Tip Temperature 300° C Continuous soldering	Solder Temperature 250° C	Ramp Profile Rate: 1.5° C/s Peak: 240° C 50s above 227° C

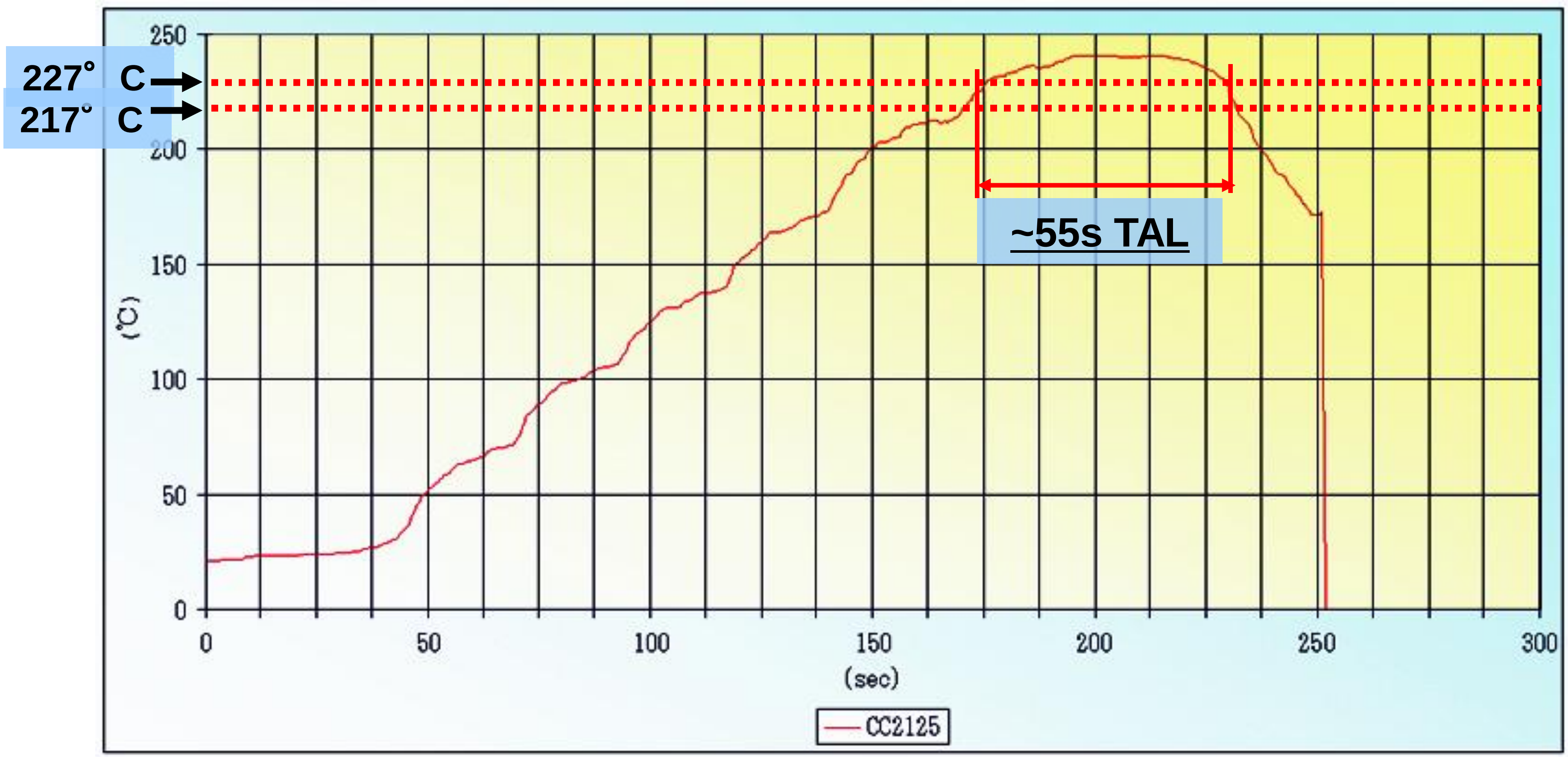
Dip Soldering Method



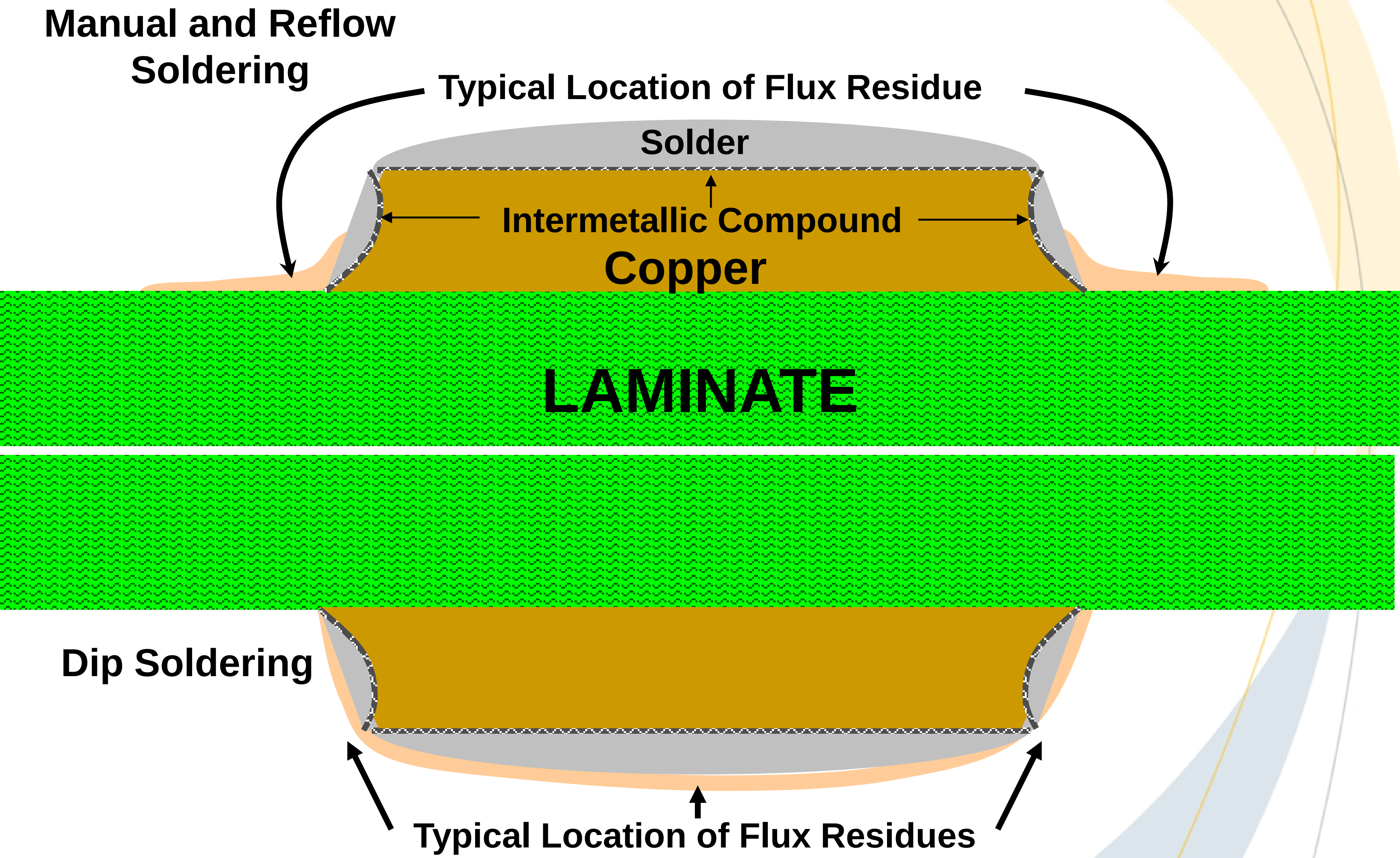
A, B, C, D	Halogenated Core Flux
E	Halogen-free Core Flux
F	Halogenated Liquid Flux
G	Halogenated Liquid Flux
H	Halogenated Paste Medium
I, J	Halogenated Core Flux
K	Halogenated Paste Medium

SOLDERING METHODS

Solder Paste Reflow Profile



DISTRIBUTION OF FLUX RESIDUE



TYPICAL TRACE CROSS-SECTION

Dip Soldered

Very Little Flux Residue Left on Traces

TYPICAL TRACE CROSS-SECTION

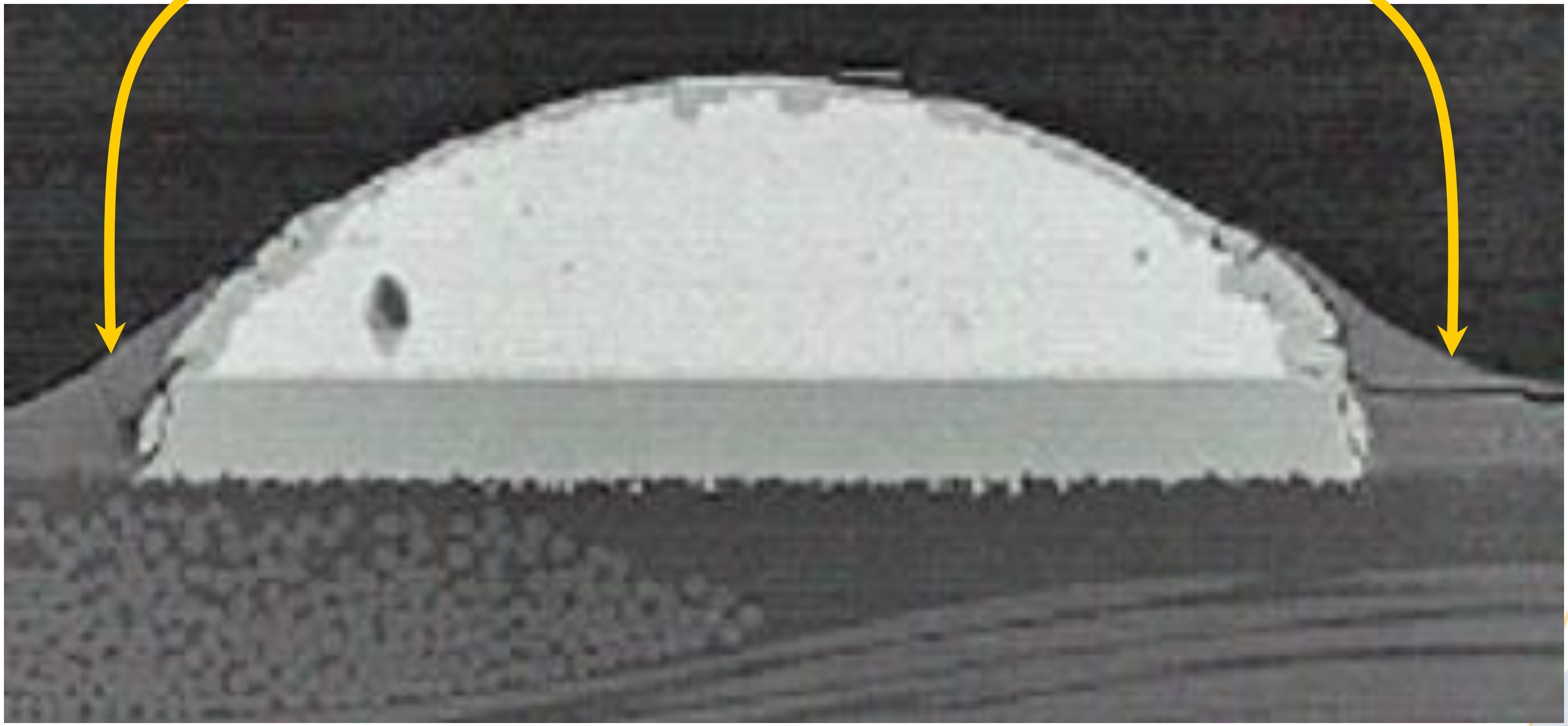
Manual Soldered

Small Volume of Flux Residue

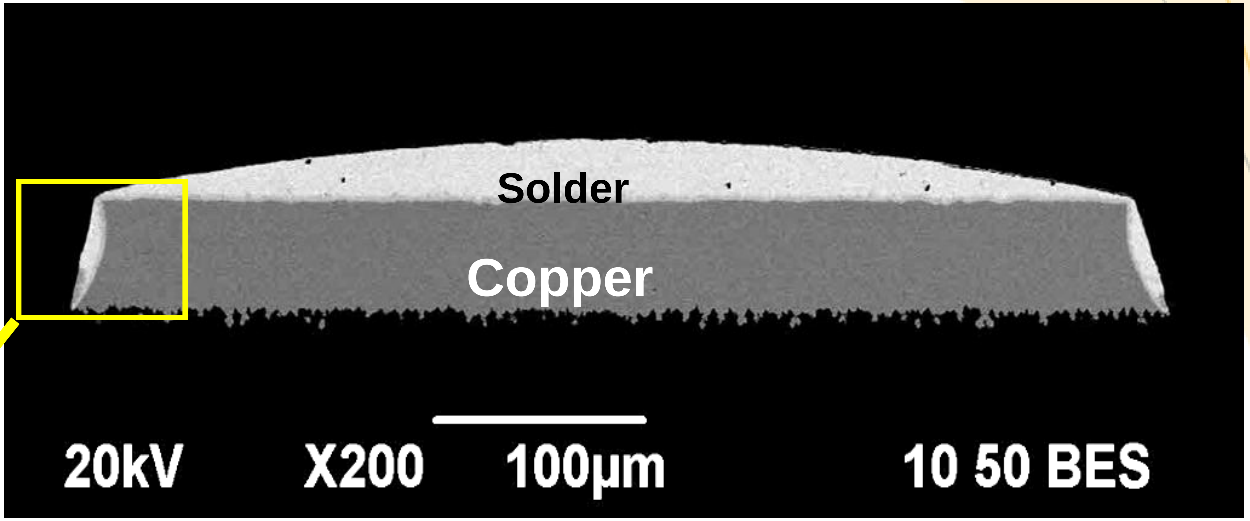
TYPICAL TRACE CROSS-SECTION

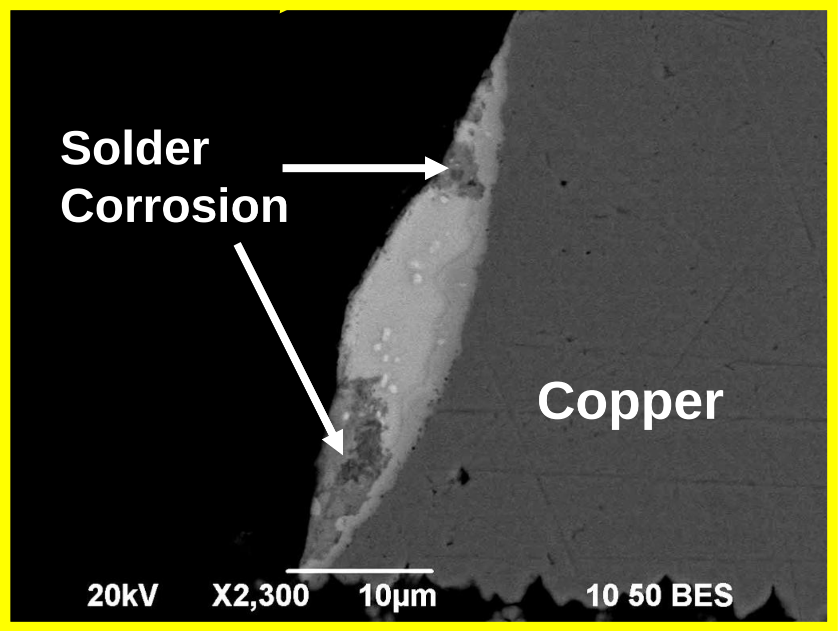
Reflow Soldered

Large Volume of Flux Residue



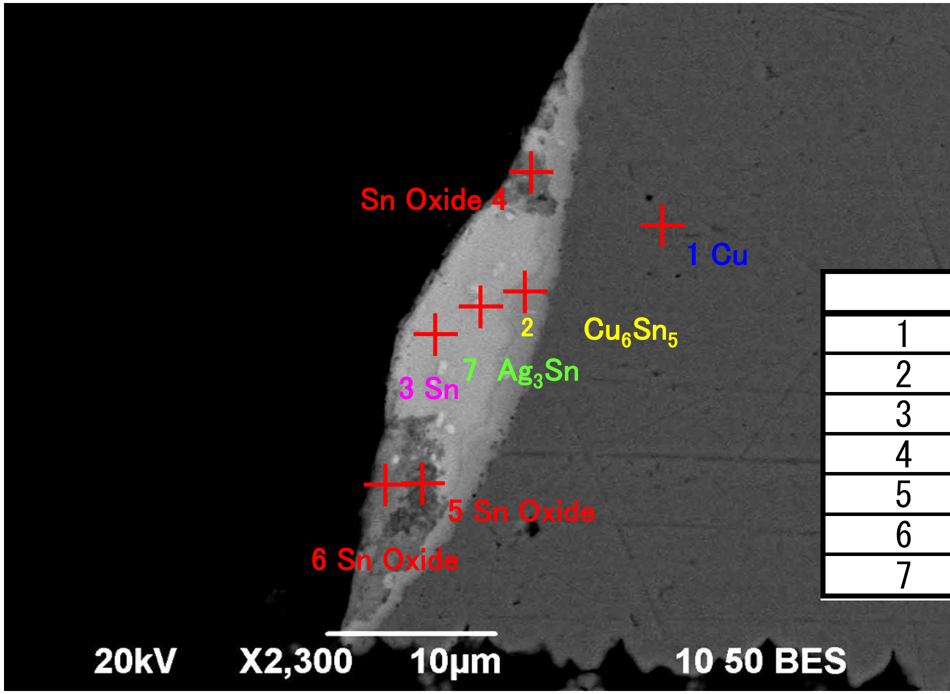
TYPICAL SOLDER CORROSION





EDX Analysis

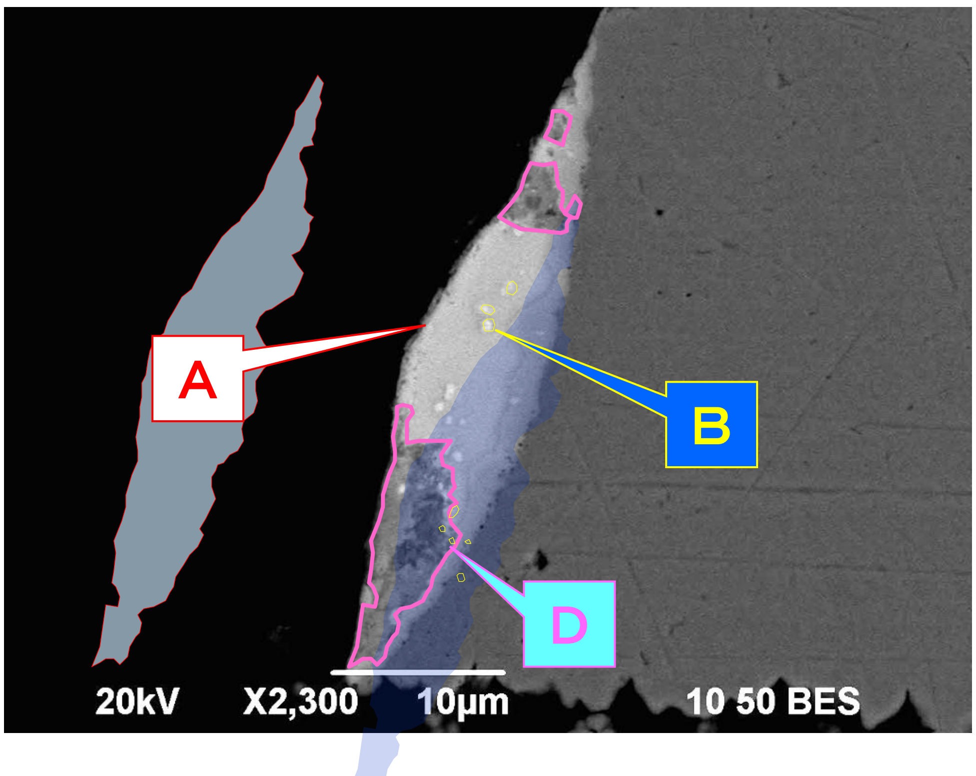
ANALYSIS OF CORRODED SOLDER



	Sn	Cu	Ag	O	C
1	0.28	76.77	0.17	19.41	3.37
2	45.14	31.16	1.01	20.09	2.6
3	74.79	0.78	1.66	20.48	2.28
4	68.4	3.83	4.49	19.74	3.54
5	68.07	3.61	4.91	19.62	3.79
6	71.7	2.24	1.42	20	4.64
7	67.72	1.52	9.74	19.36	1.65

QUANTIFYING CORROSION

$$\text{Corrosion}(\%) = \frac{\text{Total Corroded Area}(D)}{\text{Total Area}(A) - \text{Total Area of Intermetallics}(B)} \times 100$$



Example Calculation

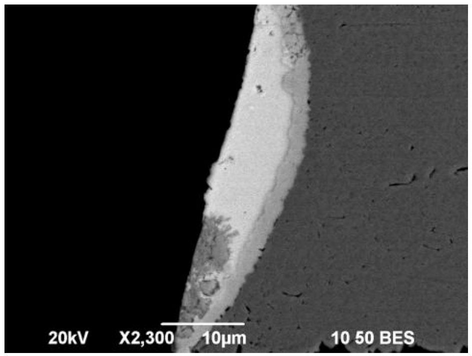
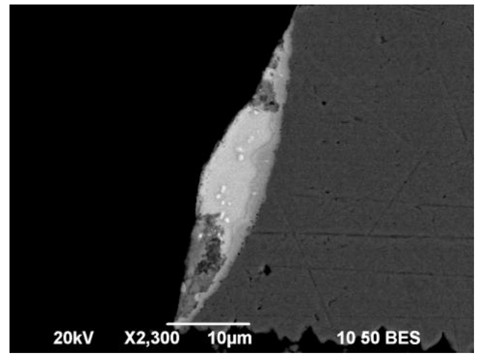
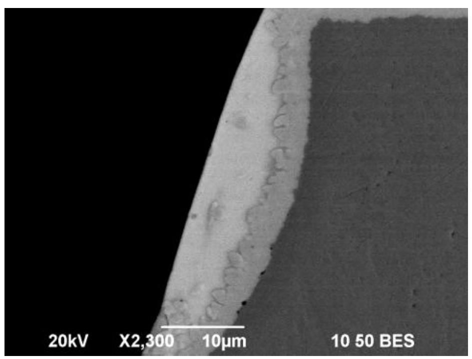
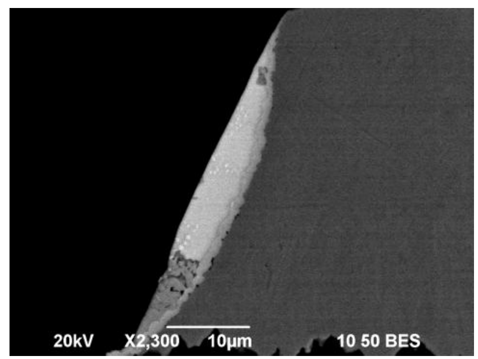
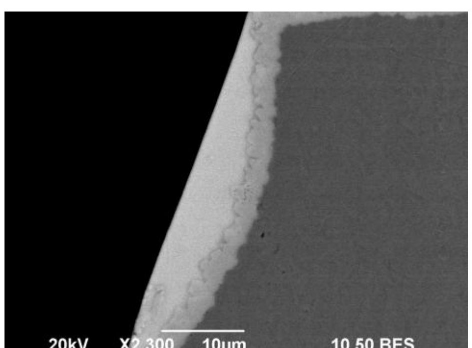
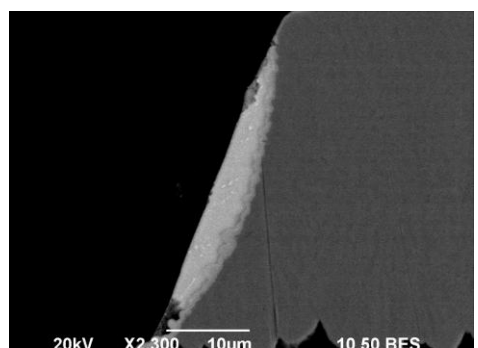
Units：μm^2

	Total Area (A)	Total Area of Intermetallics (B)	(C) ＝(A)－(B)	Total Corroded Area (D)	% Corrosion D/C
Measured Values					
Total					

Corrosion＝41%

CORROSION & ENVIRONMENT-1

Extent of Corrosion as a Function of Environment and Time

	Dip Soldered SN100C（Flux F）	Dip Soldered SAC305（Flux F）	Extent of Corrosion
85℃／85%RH 1000 h			Partly corroded from the edge(s)
60℃／90%RH 3000 h			Partly corroded from the edge(s) Extent of Corrosion is equal to or less than after 1000h at 85℃/85%
40℃／95%RH 3000 h			Partly corroded from the edge(s) Extent of Corrosion is less than after 3000h at 60℃/90%

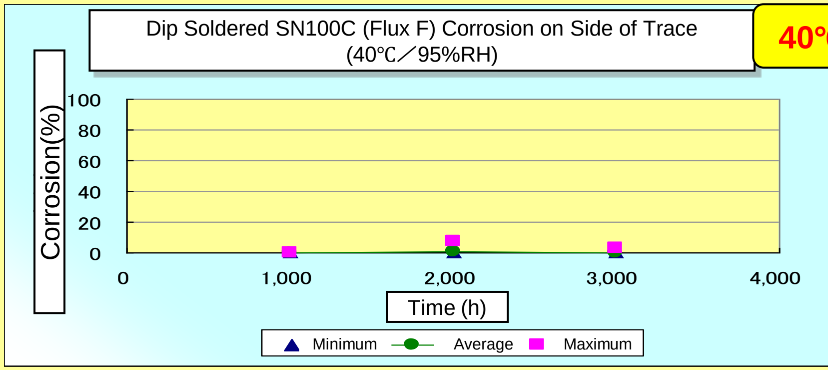
CORROSION & ENVIRONMENT-2

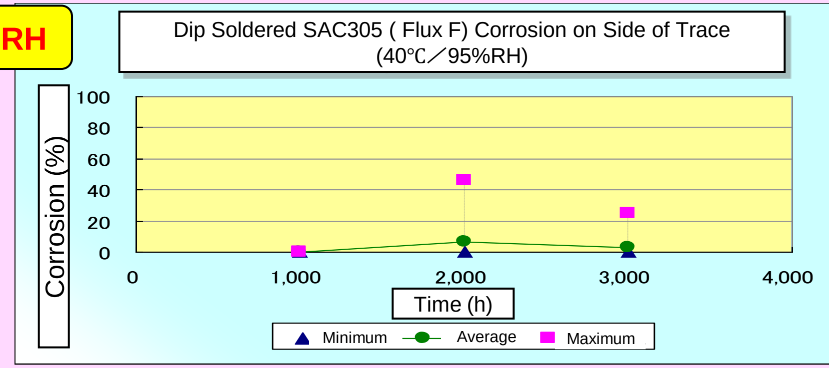
Extent of Corrosion as a Function of Environment and Time

SN100C（Flux F） ※N＝20

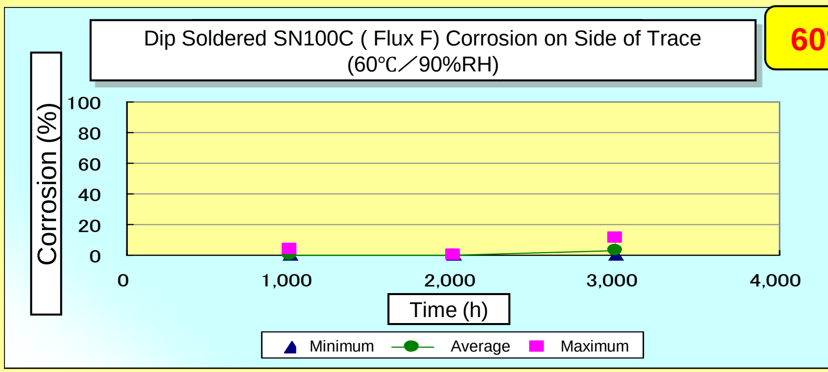
SAC305（Flux F） ※N＝20

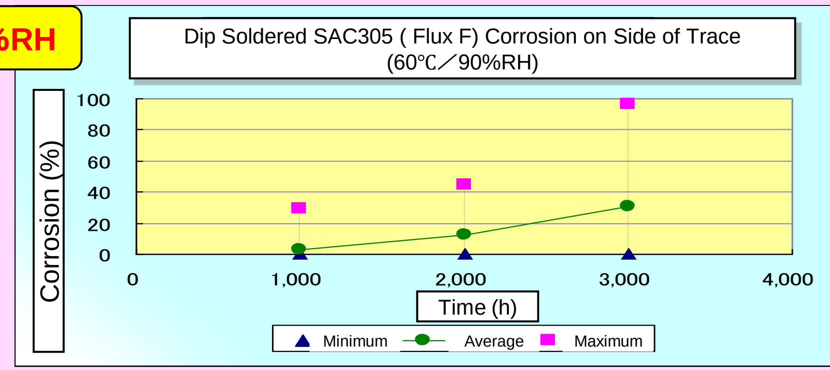
40℃／95%RH



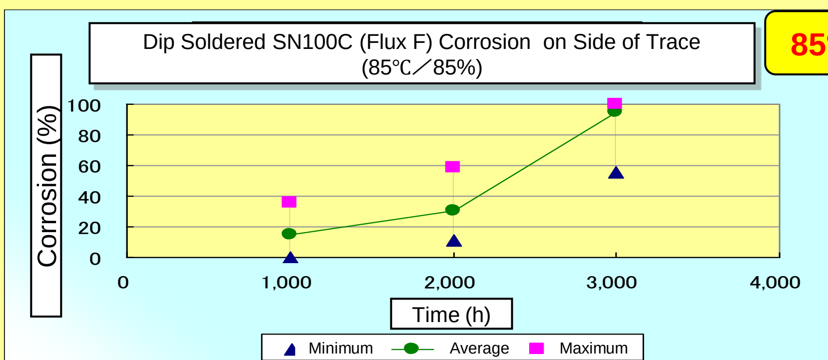


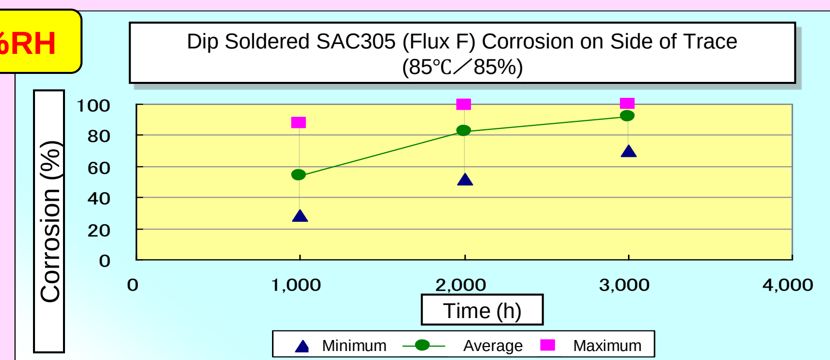
60℃／90%RH



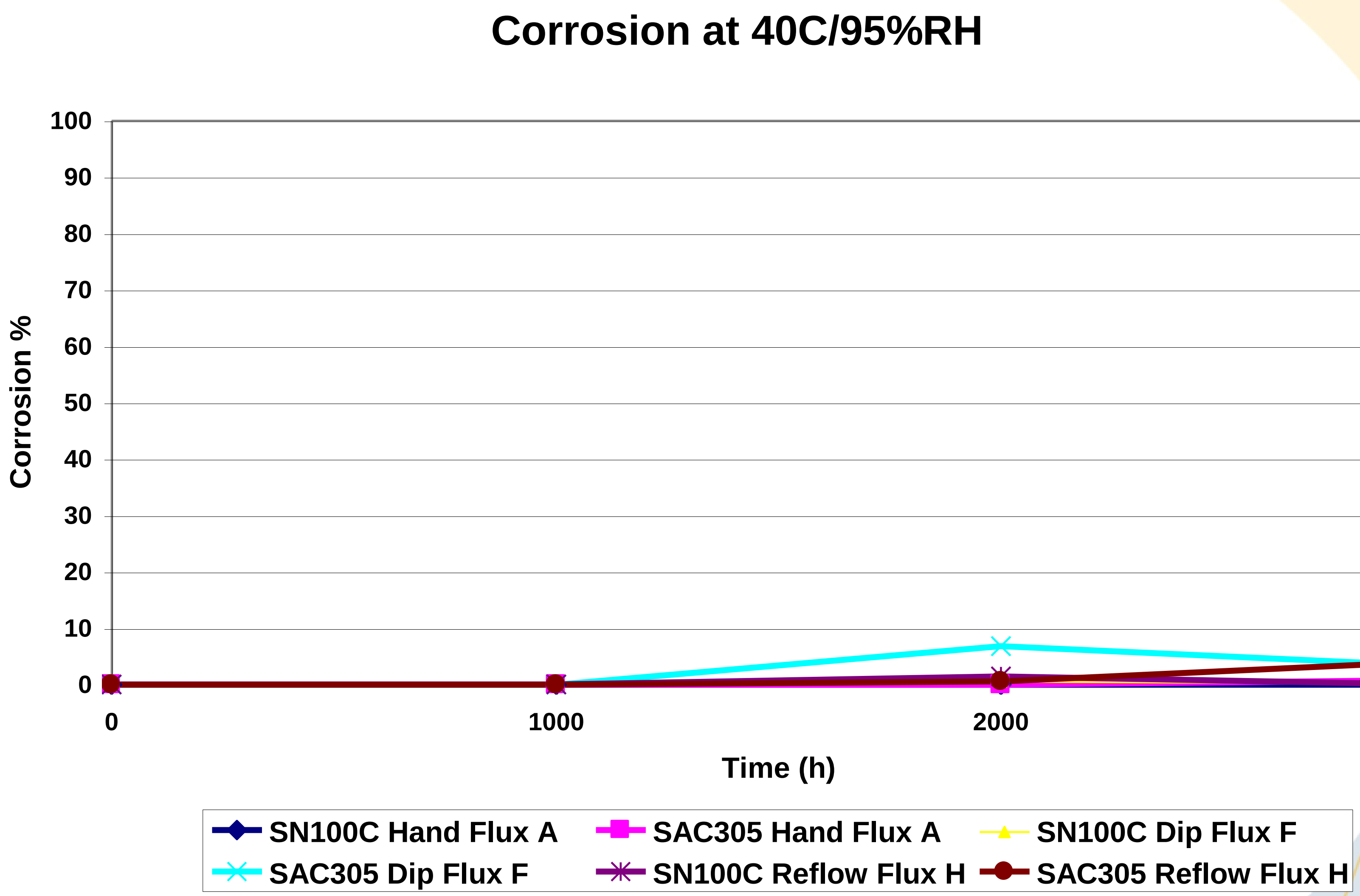


85℃／85%RH

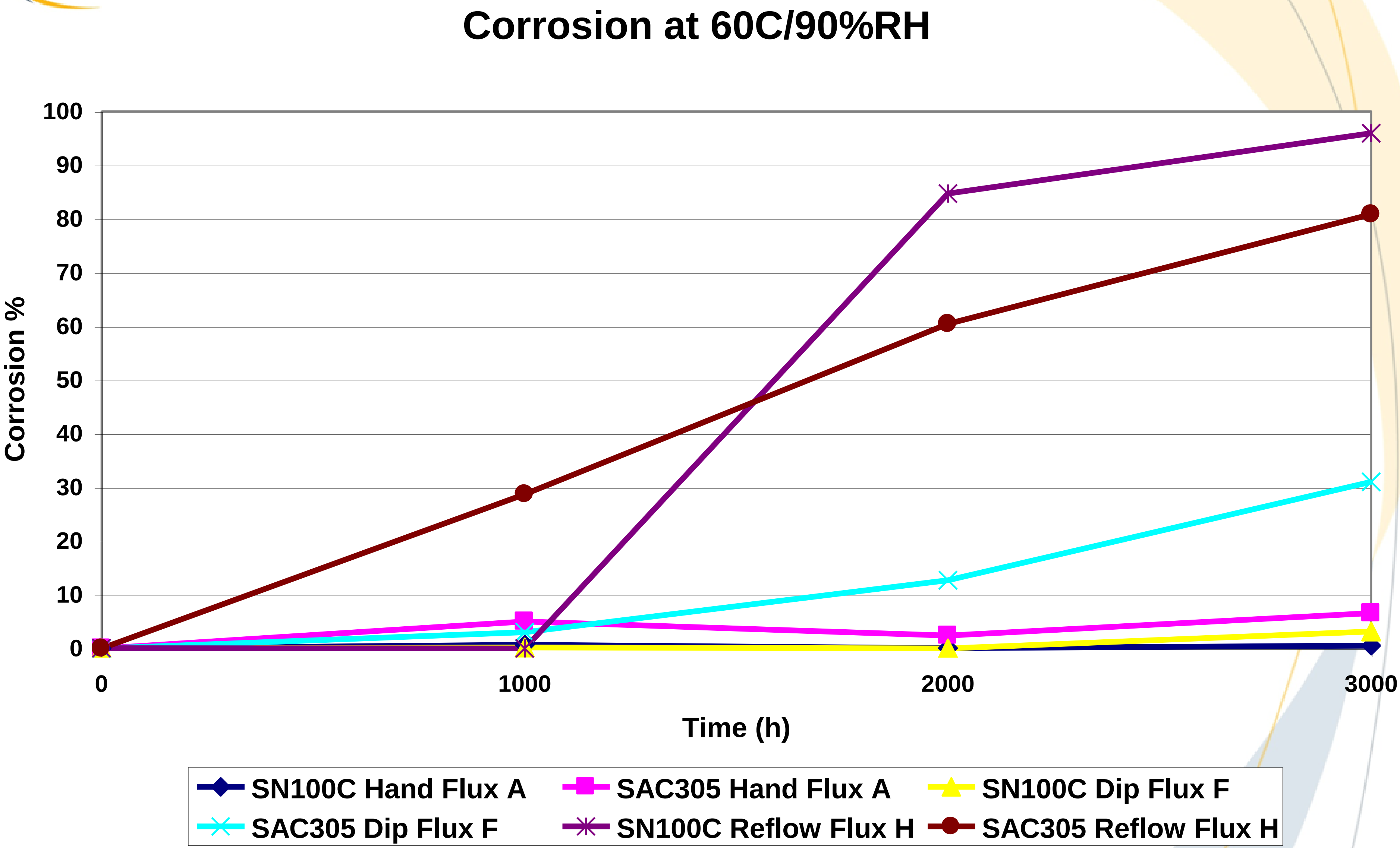




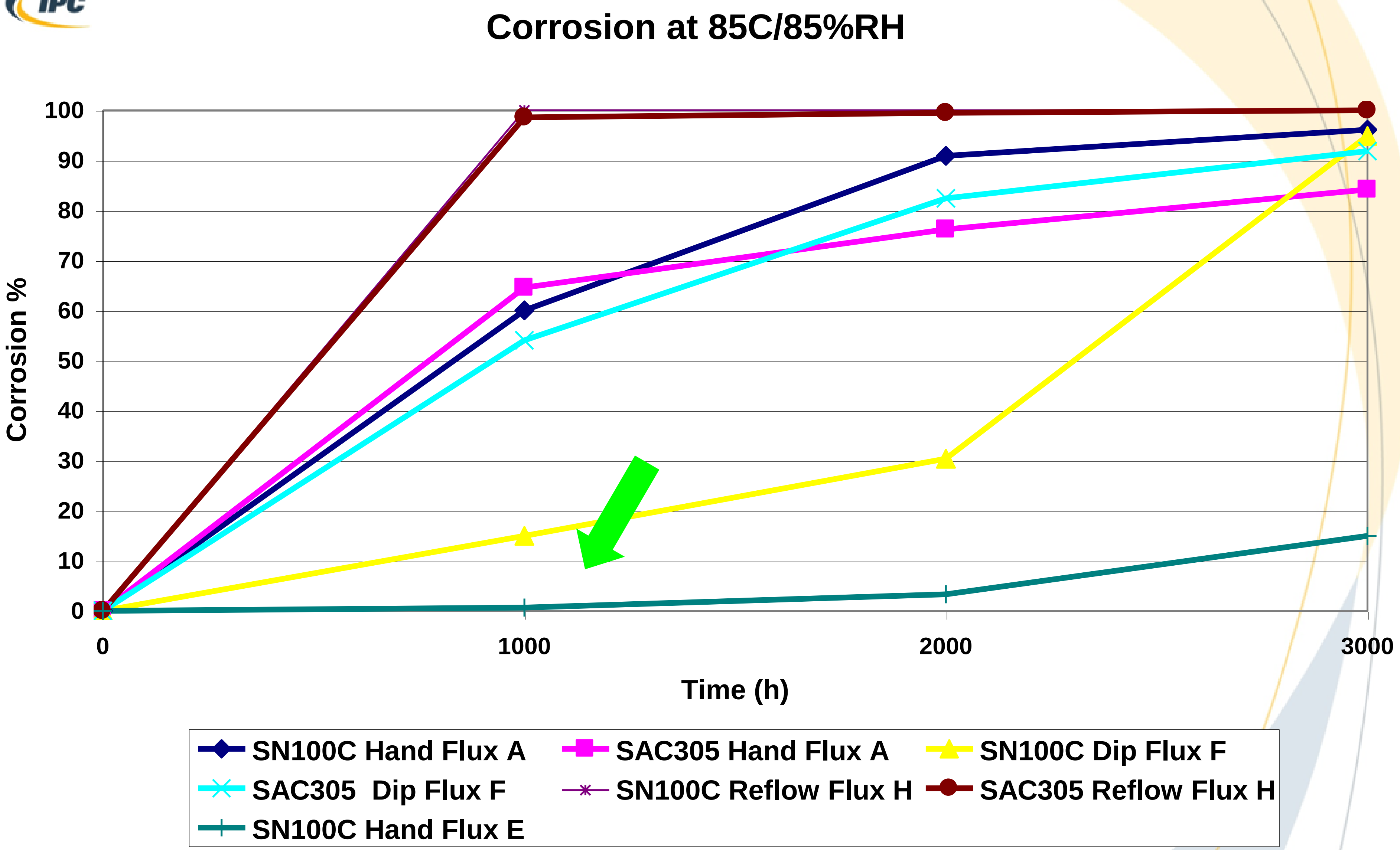
CORROSION & FLUX TYPE



CORROSION & FLUX TYPE



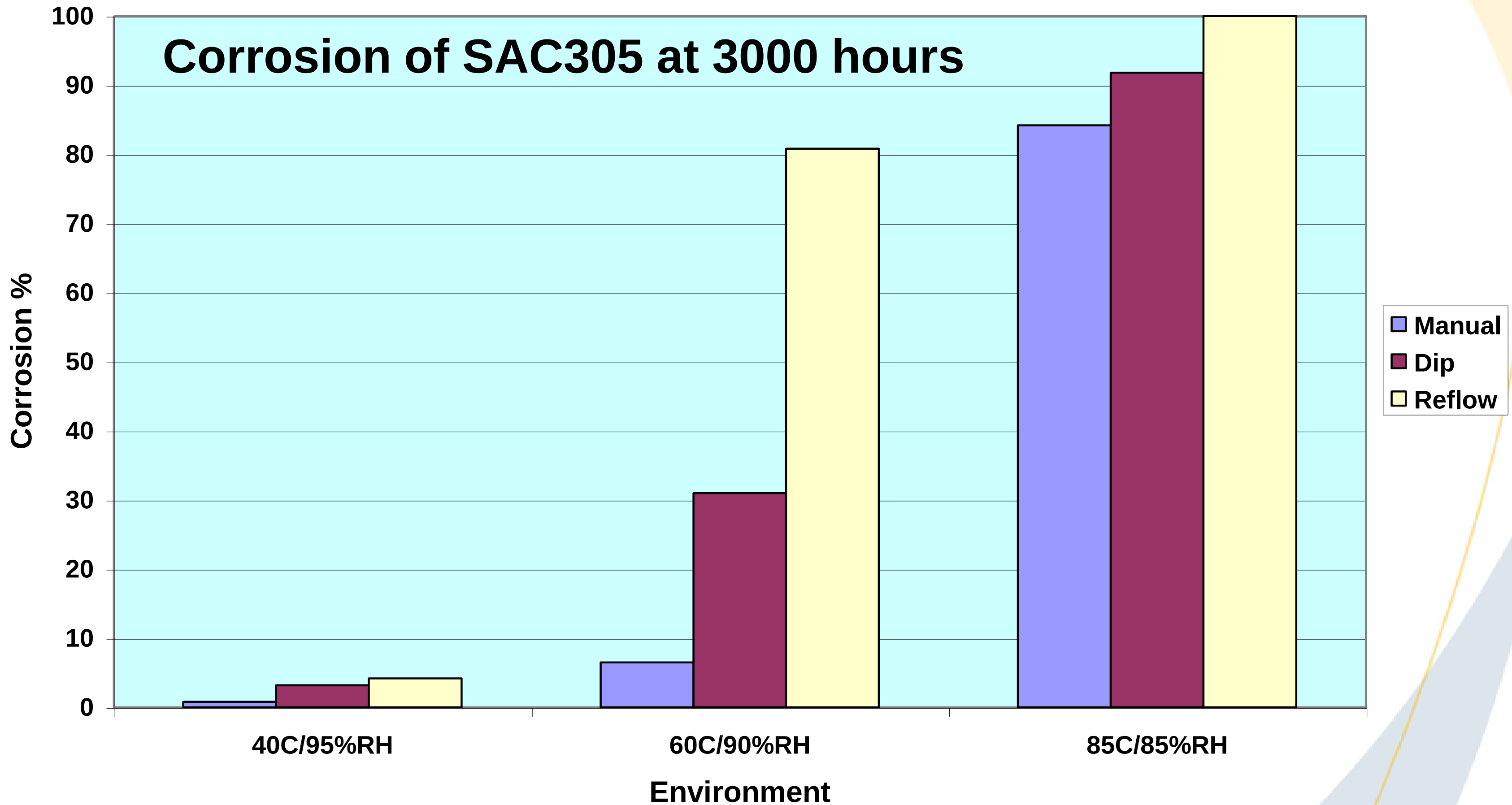
CORROSION & FLUX TYPE



CORROSION & METHOD

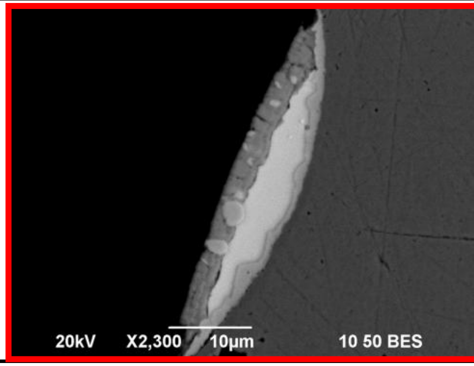
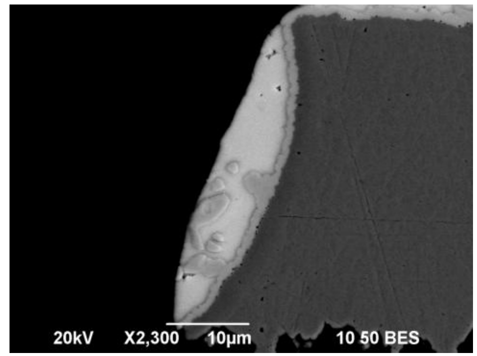
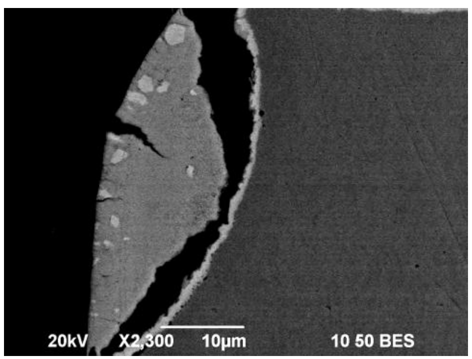
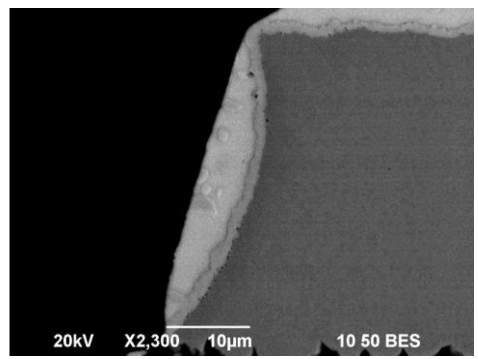
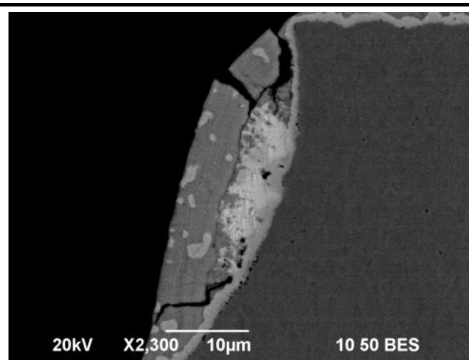
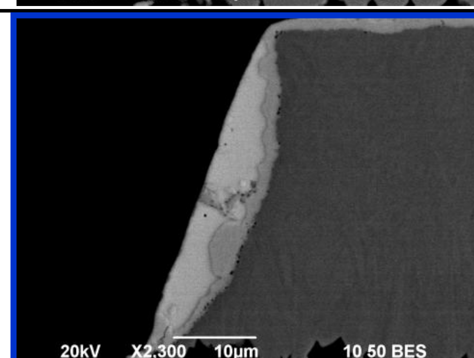
Two variable associated with soldering method

- **Flux type (chemical composition)**
- **Flux volume and distribution**



CORROSION & FLUX TYPE

Effect of Flux Type on the Extent of Corrosion

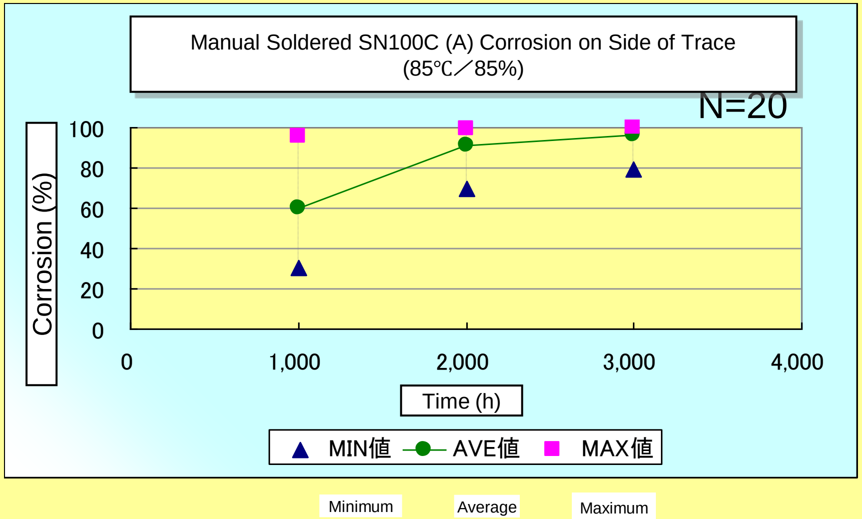
	Halogen-Activated SN100C(Flux A)	**Halogen-Free** SN100C(Flux E)	**Extent of Corrosion**
1000 h			With Halogen-Activated, only partially corroded from the edge
2000 h			With Halogen-Activated, only mild general corrosion
3000 h			Corrosion of Halogen-Free at 3000 h is less than with Halogen-Activated at 1000 h

CORROSION & FLUX TYPE

Effect of Flux Type on Extent of Corrosion as a Function of Time at 85C/85%RH

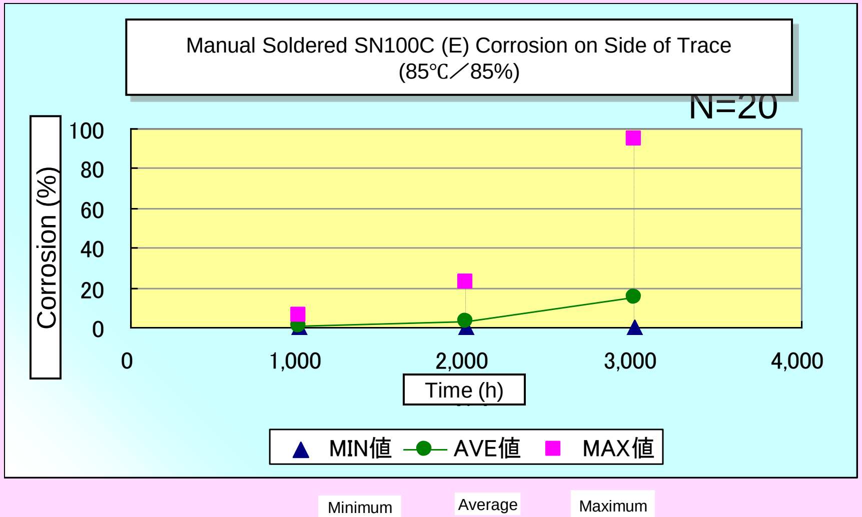
Halogen-Activated

SN100C（Flux A）



Halogen-Free

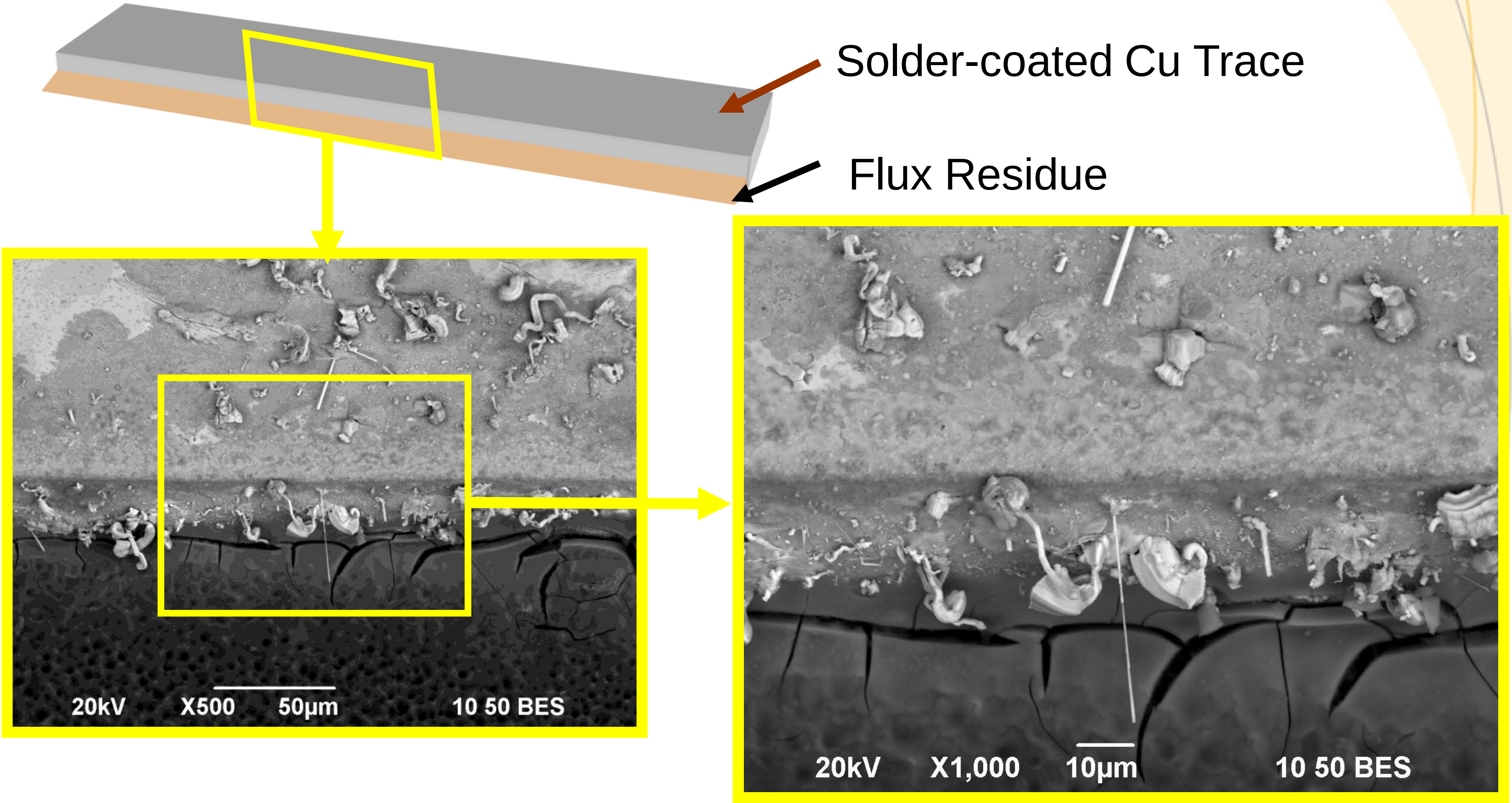
SN100C（Flux E）



Corrosion with Halogen-Free SN100C (E) is slower than with Halogen-Activated SN100C (A).

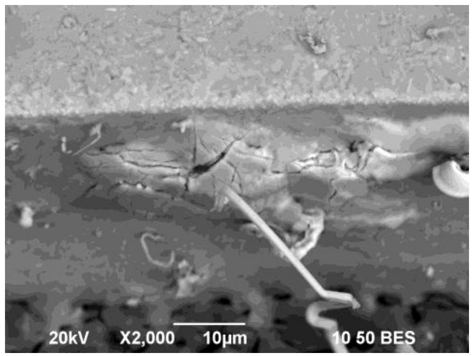
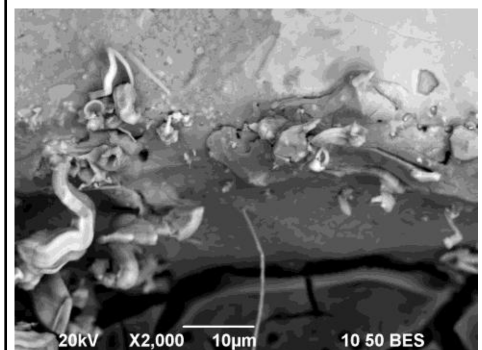
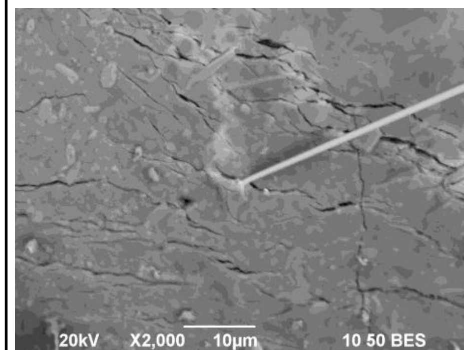
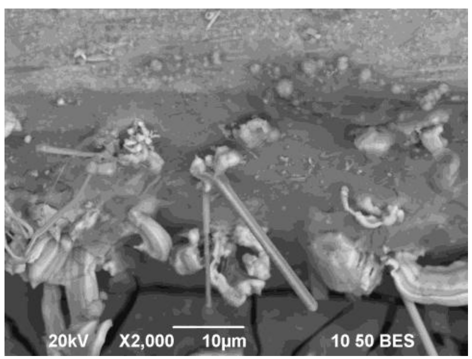
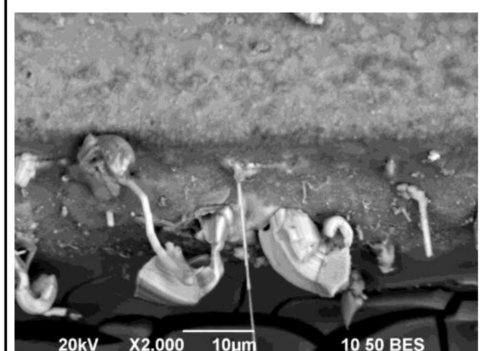
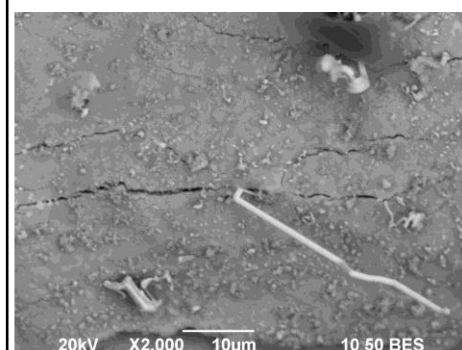
TYPICAL WHISKER GROWTH

Whiskers on SAC305
Dip soldered with liquid flux A
1000h @ 85° C/85%RH.



TYPICAL WHISKER GROWTH

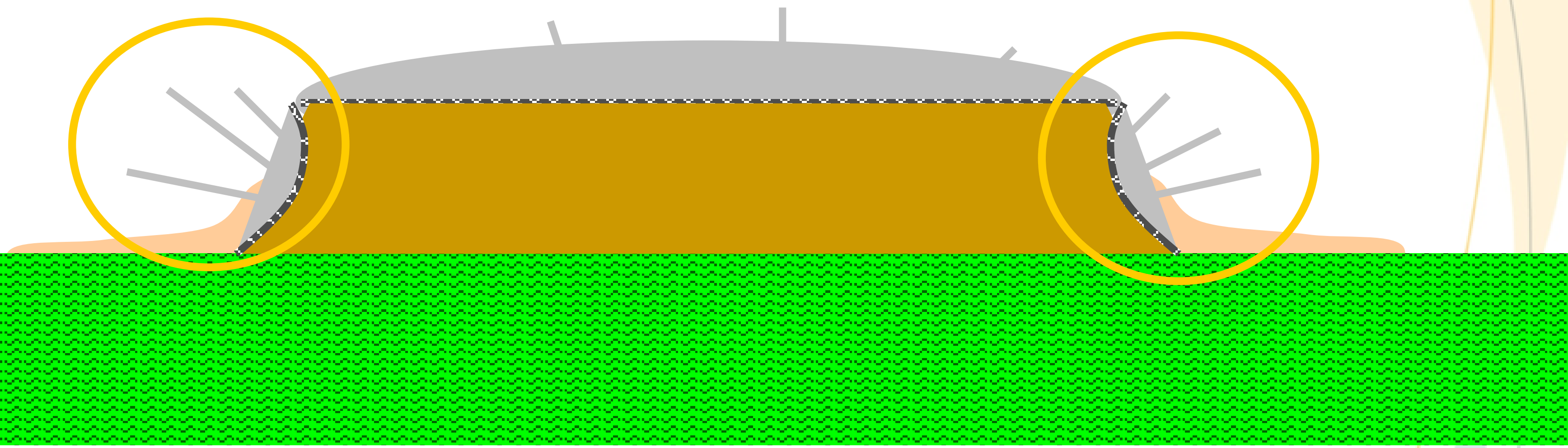
85℃／85%RH 3000 hrs

	Manual Soldering	Dip Soldering	Reflow Soldering
SN100C			
SAC305			

Whiskers growing through flux residue

TYPICAL LOCATION OF WHISKERS

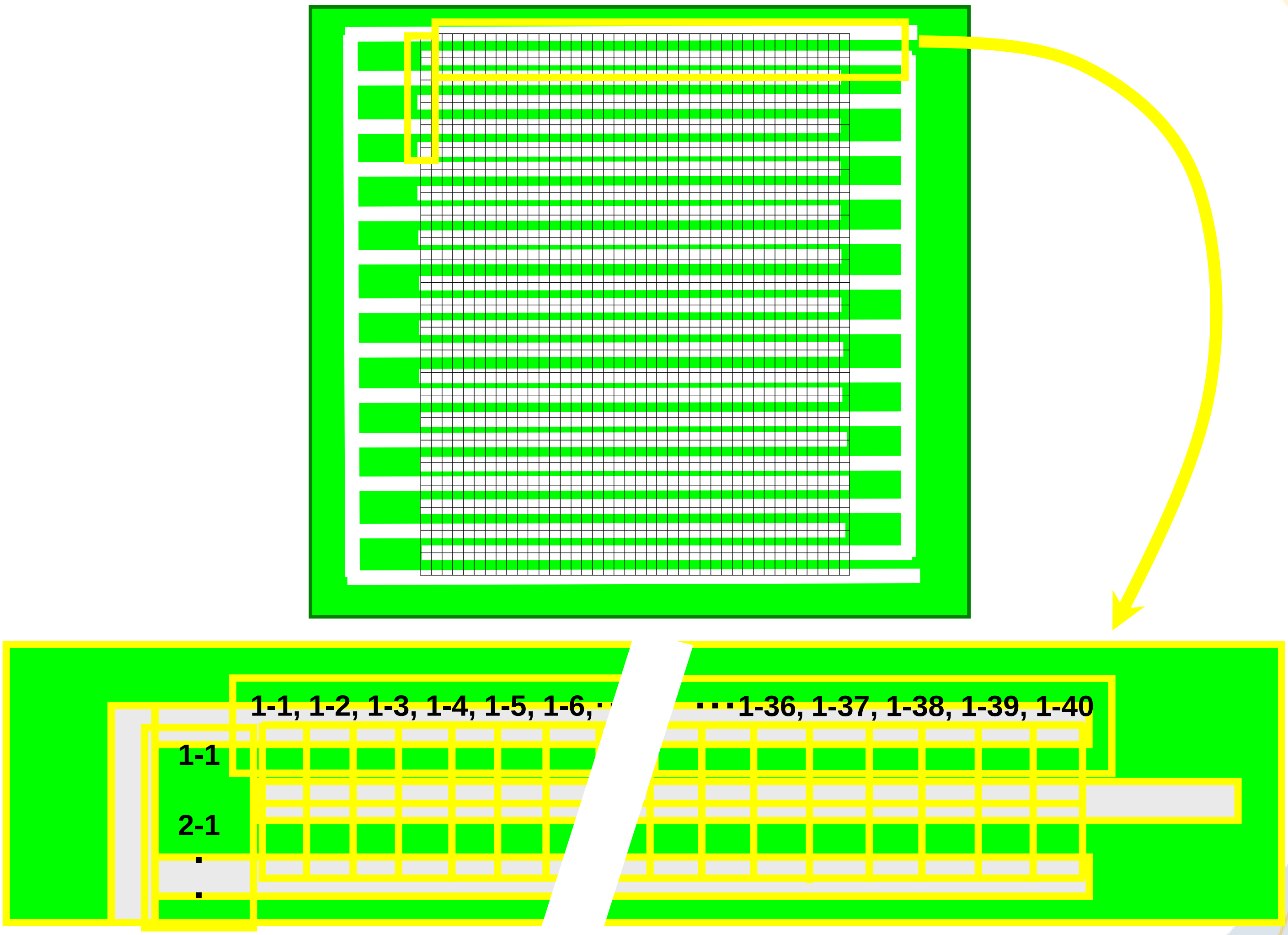
Greatest Incidence of whiskers on the edges of the traces



This is probably because that is where there is the greatest concentration of flux residue

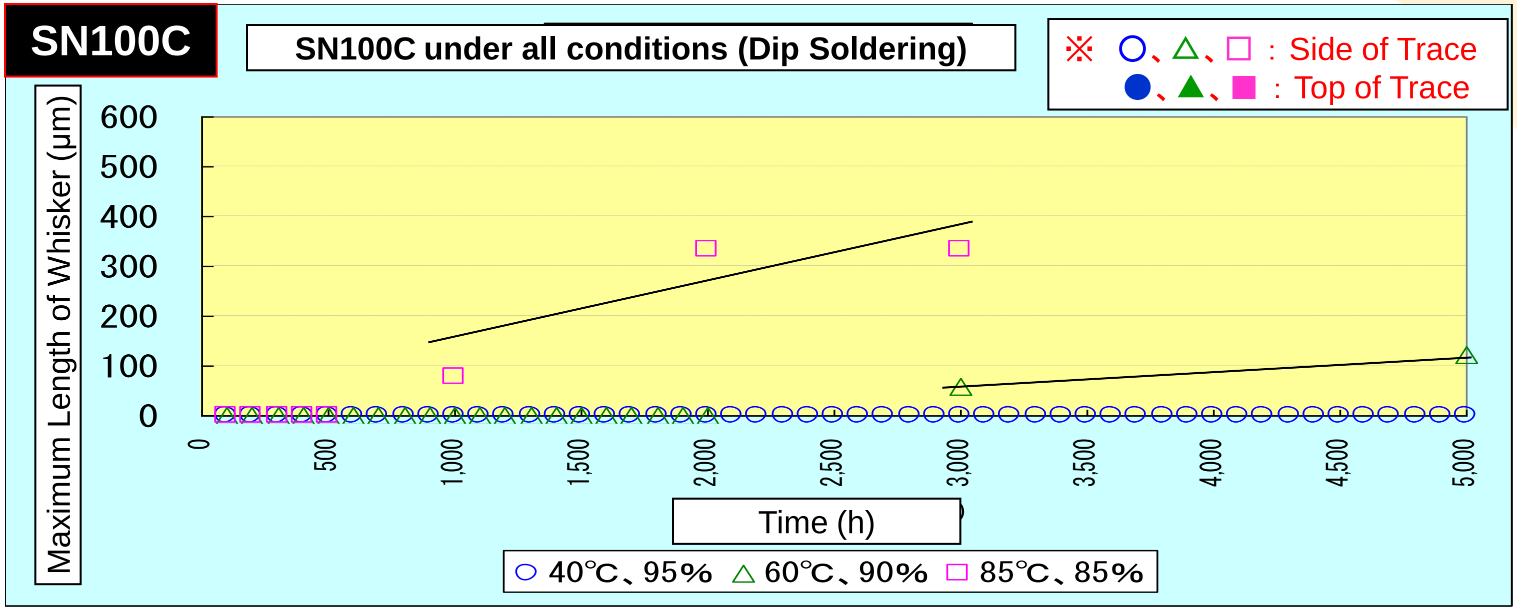
OBSERVING WHISKERS

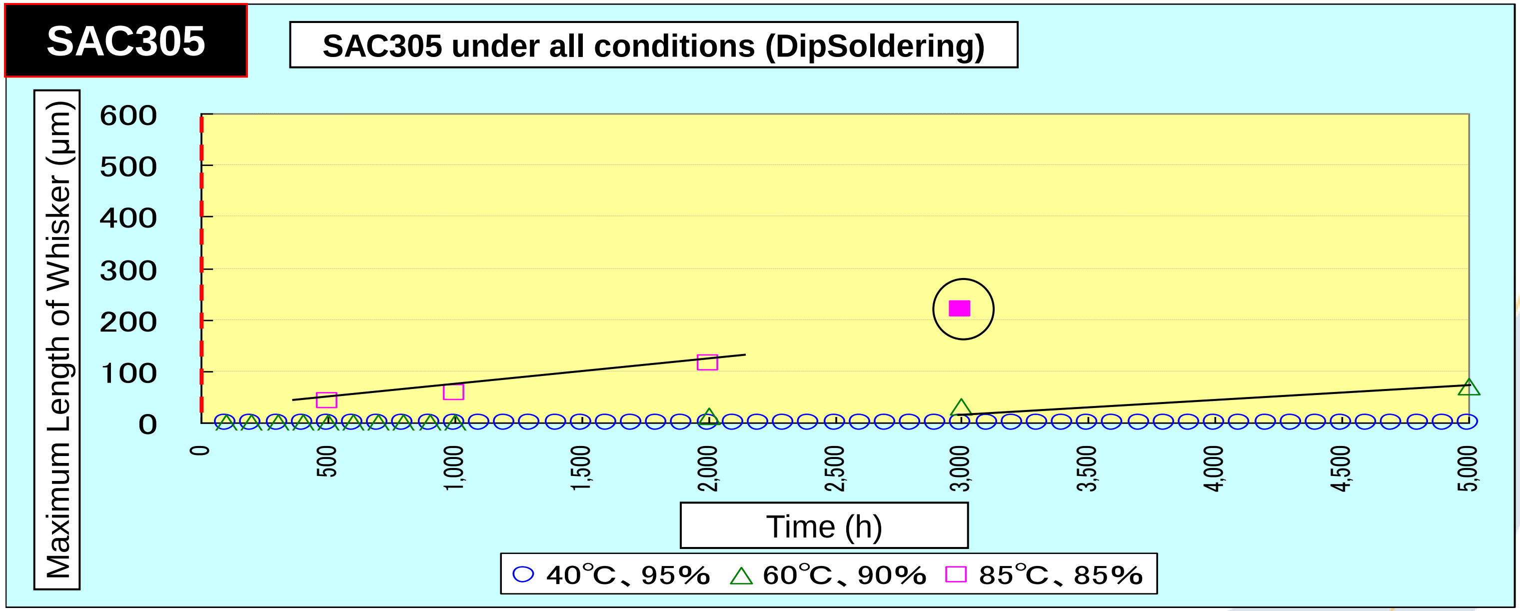
Virtual matrix of 24 lines × 40 rows



WHISKER LENGTH & ENVIRONMENT

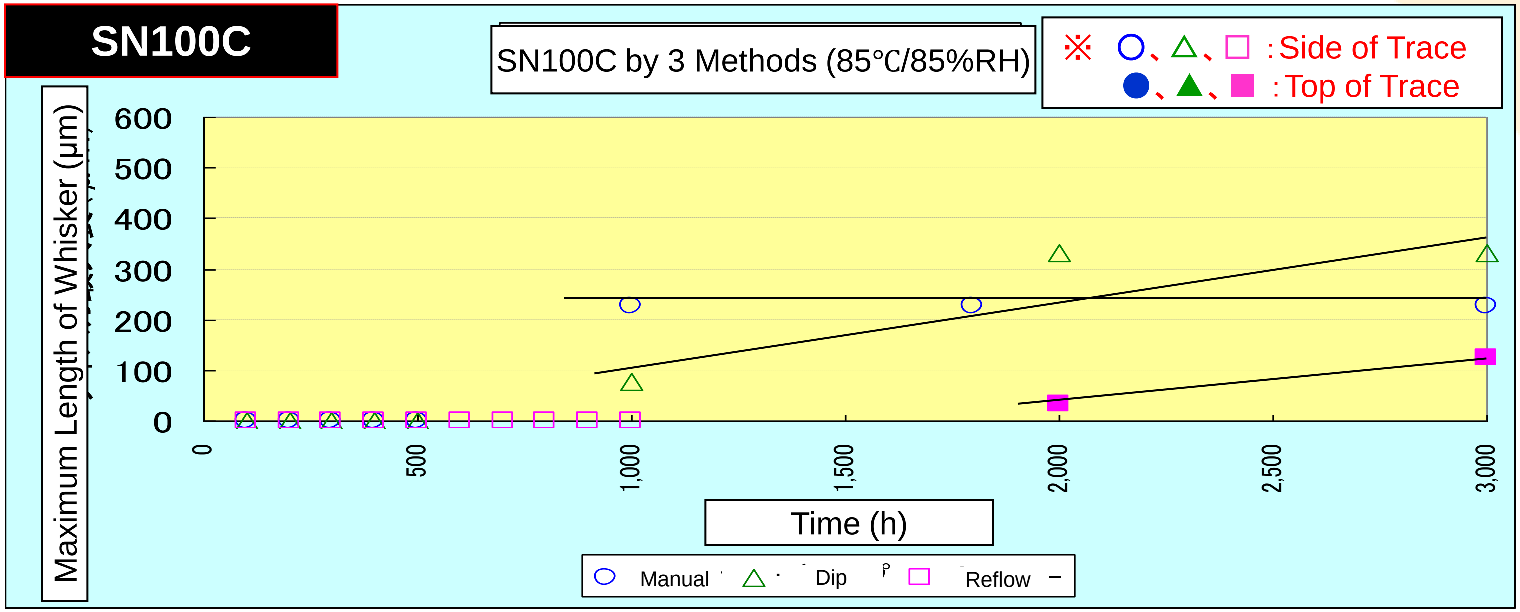
Maximum Whisker Length as a Function of Environment and Time

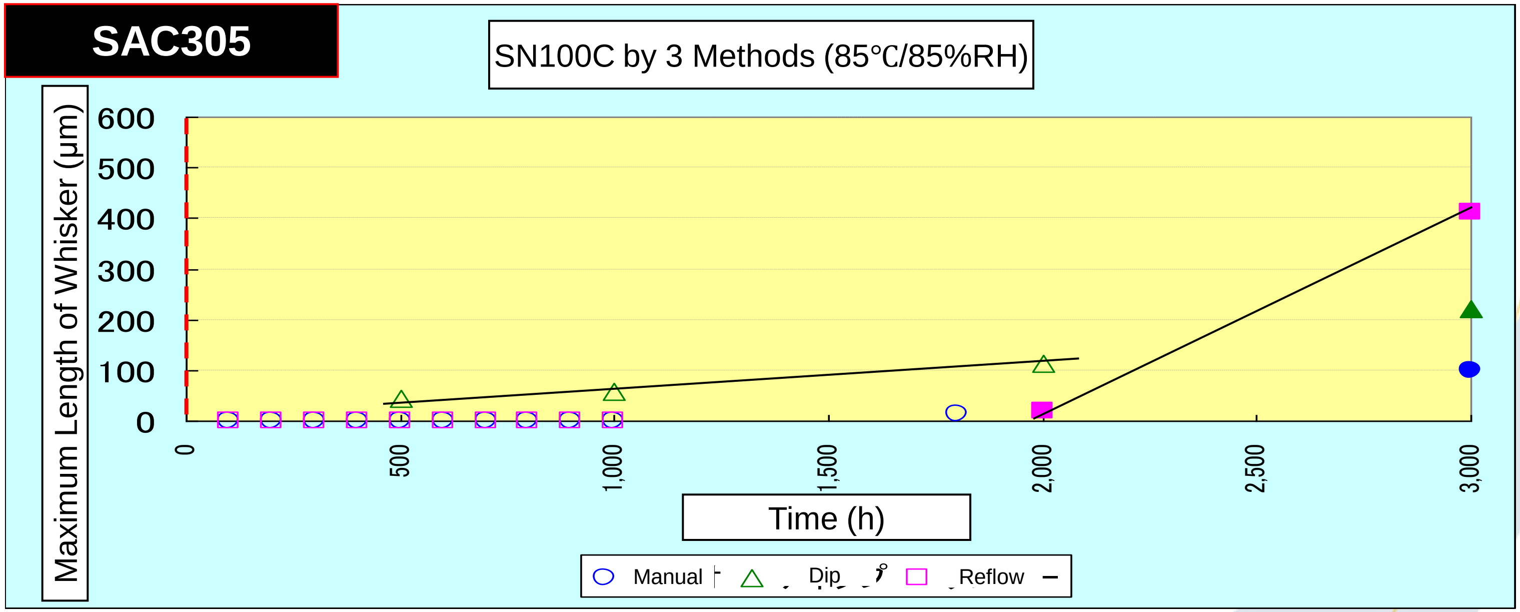




WHISKER LENGTH & METHOD

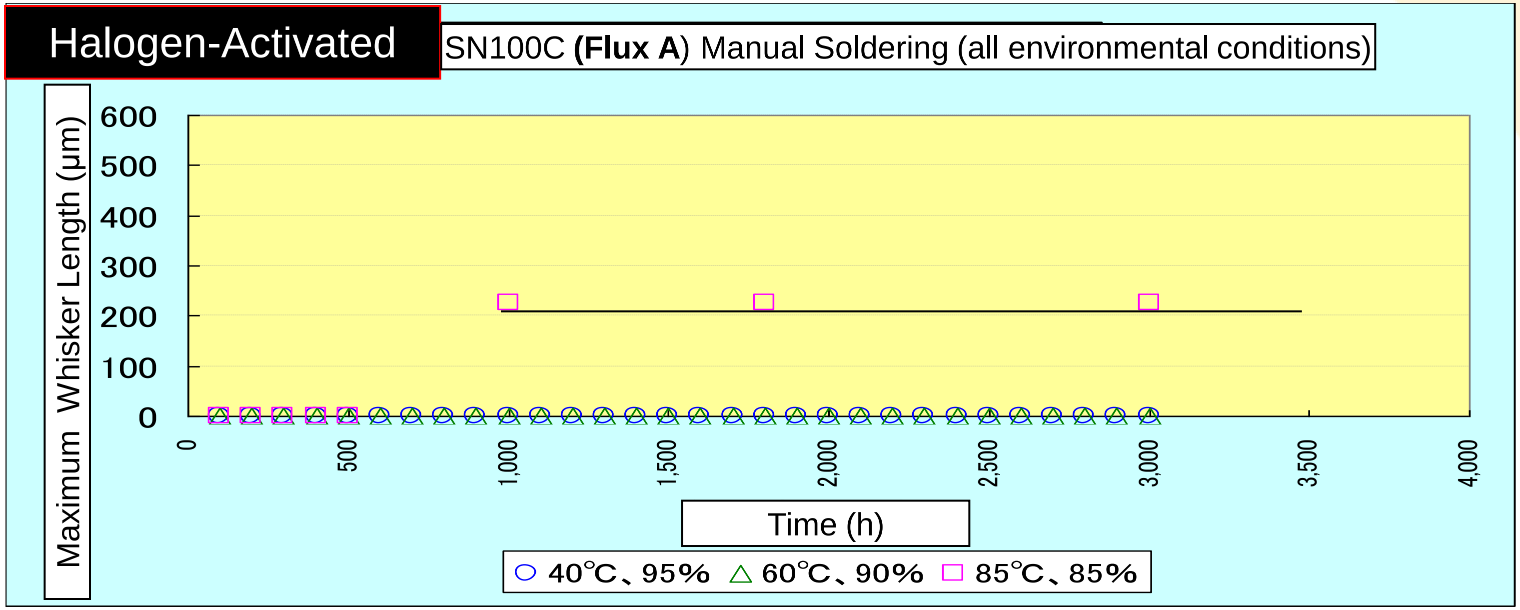
Maximum Whisker Length as a Function of Time at 85° C/85%RH & Soldering Method

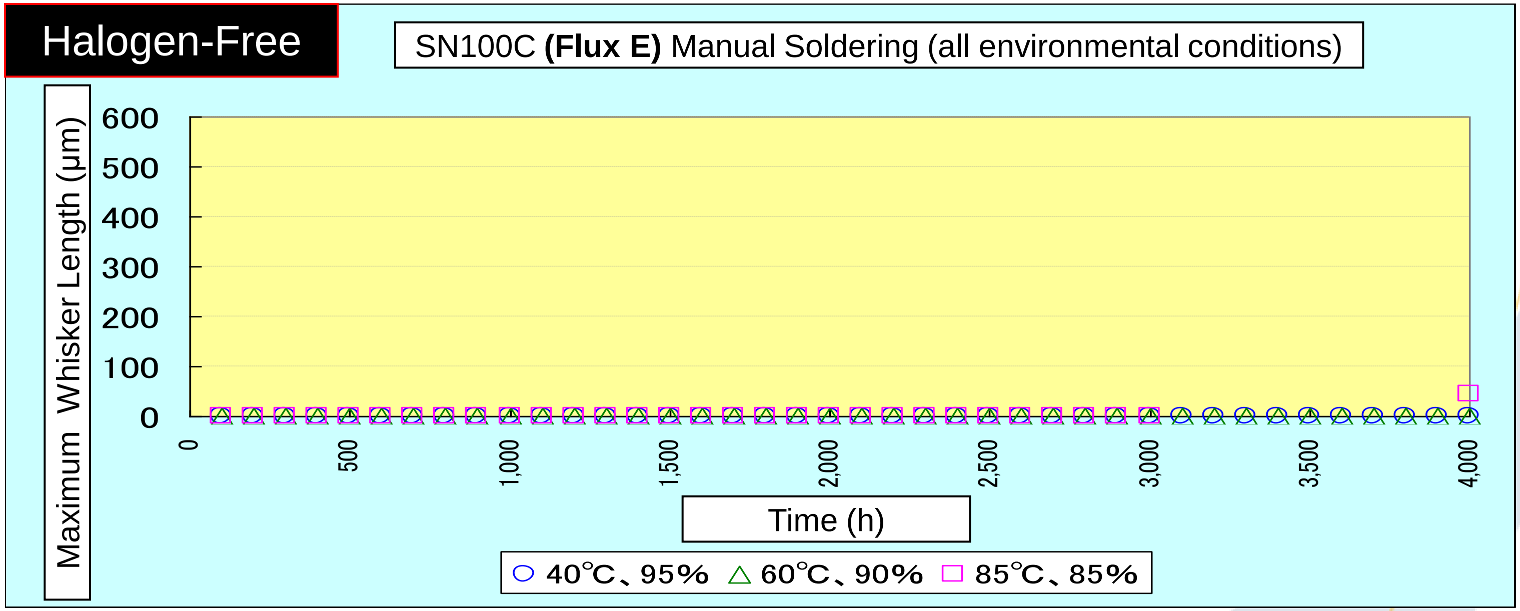




WHISKER LENGTH & FLUX TYPE

Maximum Whisker Length as a Function of Environment and Time





INCUBATION TIME & ENVIRONMENT

Effect of Environment on Time to First Whisker

Condition	SN100C	SAC305	Comparative Incubation Period
85℃/85%RH	500～1000h	～500h	1 （～500 h）
60℃/90%RH	2000～3000h	1000～2000h	~x3 （1000～2000 h）
40℃/95%RH	~≥5000h	5000h	≥x10 （~5000 h）

At 60℃/90%RH it takes approximately 3 times longer for the first whisker to appear and at 40℃/95%RH approximately 10 times longer than it does at 85℃/85%RH.

INCUBATION TIME & SOLDERING METHOD

Effect of Soldering Method on Time to First Whisker

Soldering Method	SN100C	SAC305	Comparative Incubation Period
Dip	500～1000h	～500h	1 （～500h）
Manual	500～1000h	1000～1800h	~x1.5 （500～1000 h）
Reflow	1000～2000h	1000～2000h	~x3 （1000～2000 hrs）

Ranking of soldering method by incubation period (shortest to longest) at 85℃/85%RH

Wave（1） ＜ Manual（~1.5）＜ Reflow（~3）

INCUBATION TIME & FLUX

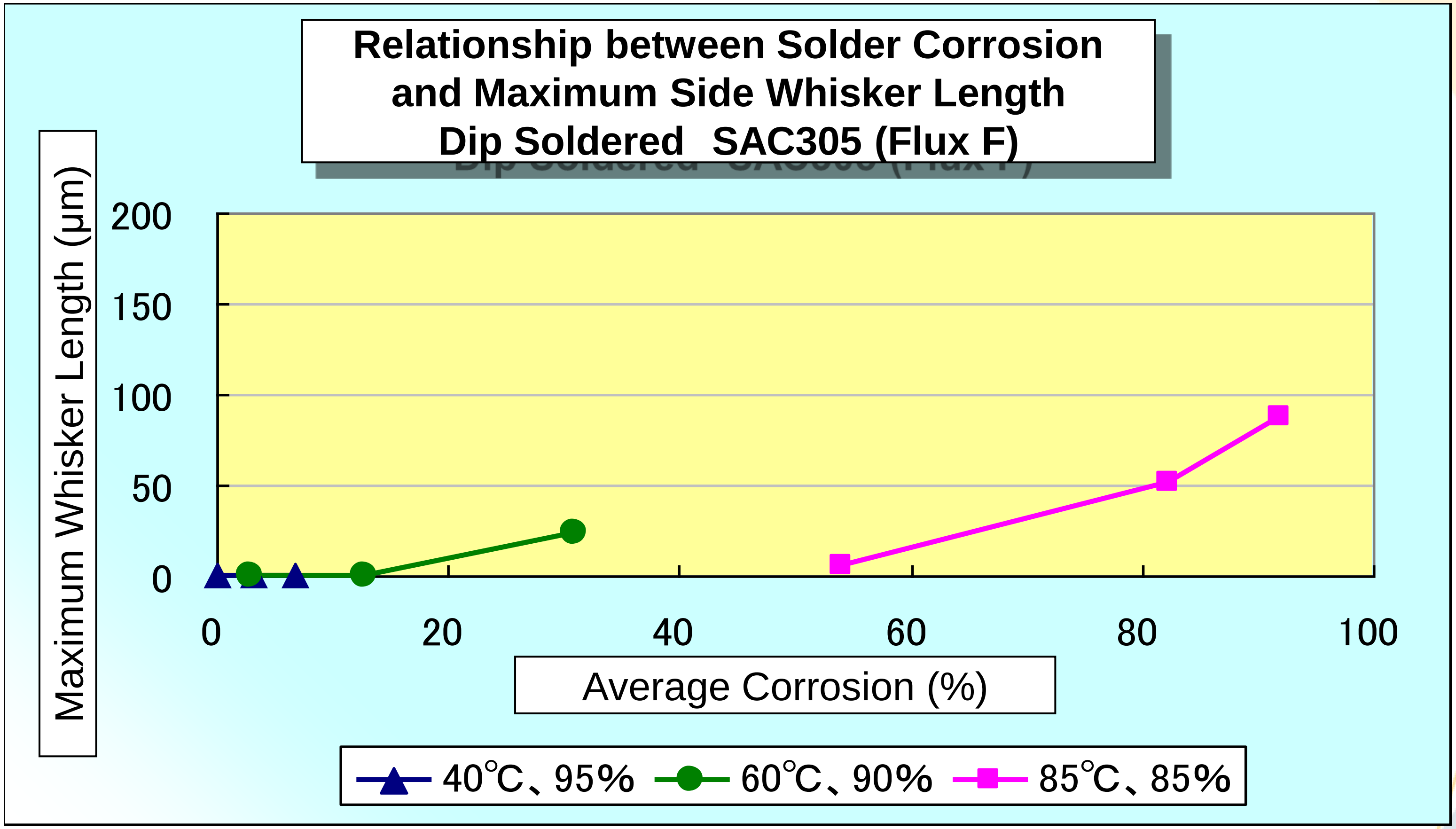
Effect of Flux Type on Time to First Whiskers

Type of Flux	SN100C	Comparative Incubation Period
Halogen-Activated SN100C （Flux A）	500～1000 h	1 （500～1000 h）
Halogen-Free SN100C （Flux E）	3000h～4000 h	~x5 （3000～4000 h）

Time to first whisker with halogen-free flux-cored wire SN100C (Flux E) is approximately 5 times longer than with halogen-activated flux-cored wire SN100C (Flux A) in 85℃/85%RH.

WHISKER LENGTH & CORROSION

Maximum Whisker Length as a Function of the Extent of Corrosion



Maximum whisker length is proportional to the extent of solder corrosion

CONCLUSIONS

- A relationship between the incidence of whiskers and the extent of corrosion
- Increased volume of corrosion product generates compressive stress
- The main factors determining the extent of corrosion are
  - Chemical activity of flux residues **(Halogen-free vs Halogen-activated)**
  - Heat and humidity **(Maximum whisker growth occurred at 85° C/85%RH)**
  - Alloy composition **(Silver-free less than silver-containing)**
- The primary effect of the soldering method on corrosion and hence on whisker growth is the chemistry of the flux used in the method.
- A secondary effect of the soldering method is the volume and distribution of the flux.

FACTORS IN CORROSION-DRIVEN WHISKERING

SOLDERING METHOD

FLUX TYPE

DISTRIBUTION OF FLUX RESIDUES

EXTENT OF CORROSION

LOCATION of CORROSION

FIRST INCIDENCE OF A WHISKER

WHISKER GROWTH

LONGEST WHISKER

WHISKER- INDUCED SHORT CIRCUIT

Heat and Humidity are powerful corrosion accelerators.

Most corrosion wth 85° C/85%RH

FUTURE WORK

WHISKER-SAFE FLUXES?

- Incidentally in this study it was found that a particular commercial halogen-free solder wire core flux did not induce whisker growth that exceeded the JEITA criterion of no whisker >50μm after 1000 hours exposure to 85° C/85%RH.
- Other commercial halogen-free fluxes did not meet that criterion
- A study is now underway to determine what features of that flux reduced its tendency to promote whisker growth.
- The objective of that study is to develop guidelines for the formulation of fluxes which do not promote whisker-inducing corrosion.

Thank You