SW Test Workshop
Semiconductor Wafer Test Workshop

Pulsed CCC: a Numerical Model for Vertical Probe Design

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Background and Scope

- Automotive applications are requiring increasingly more demanding testing conditions, especially in terms of high currents and high temperatures.
- Therefore it would be very valuable to be able to predict the Current Carrying Capability (CCC) of the probes in test and also in real production conditions.
- The ISMI2009 methodology is a possibility for the evaluation of the CCC in DC conditions but what about pulsed/cycling conditions?
- In the present work a series of experiments on vertical probes were carried out to understand the general behavior of the CCC under simple cycling conditions with varying:
  - Current
  - On-time
  - Duty Cycle

  for a given material and geometry.
- The data were interpreted and elaborated in the attempt to understand the trends and propose an approximation based on a small set of parameters.
- Other more complex ways to use the data are proposed.

Probe Force vs Temperature

- **A necessary condition for a good and stable electrical contact is a sufficient contact force. The probe has to guarantee a minimum force at any working temperature.**
- **The probe force is proportional to the stress σ (for a given OT): $F \propto \sigma$**
- **To prevent any plastic deformation the stress has to remain lower than the yield stress σ_y:**

$$\sigma < \sigma_y$$

- **At the same time the force has to stay higher than a certain limit, so:**

$$\sigma > \sigma_{limit\ force}$$

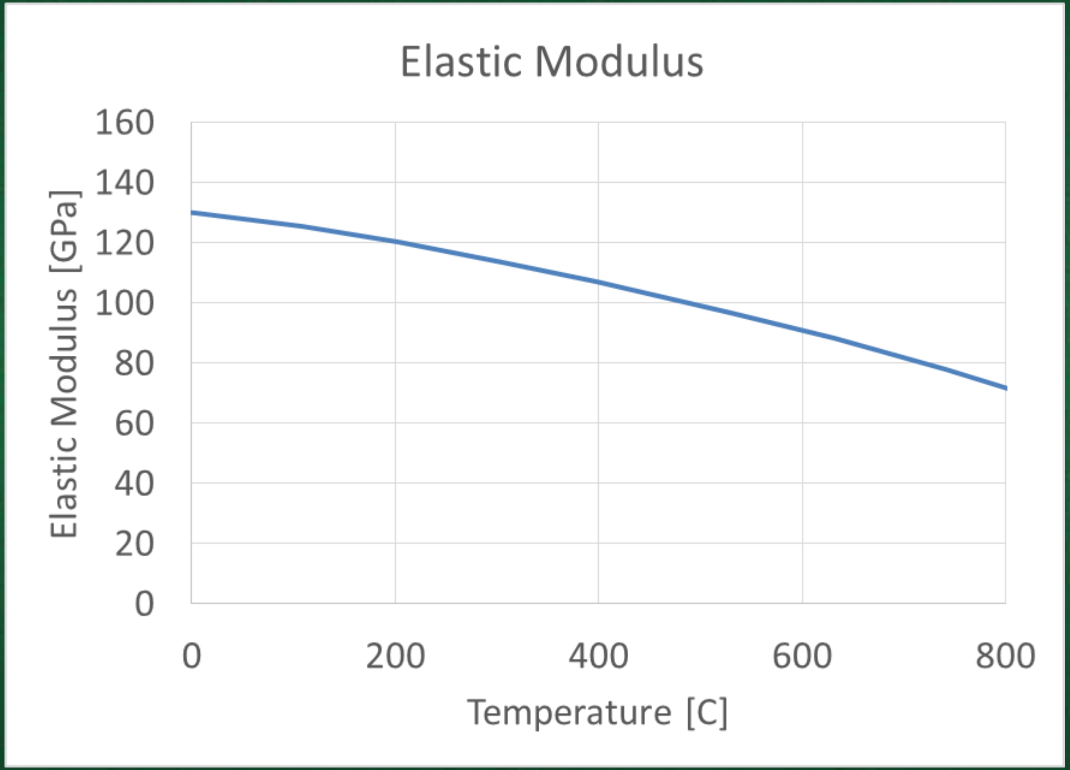
$$\sigma_{limit\ force} < \sigma < \sigma_y$$

- **The stress is the product of the elastic modulus by the elastic deformation: $\sigma = E\varepsilon_{elastic}$**
- **What happens as the Temperature increases?**
  - The elastic modulus decreases: $E = E(T)$ → σ decreases
  - The yield stress decreases: $\sigma_y = \sigma_y(T)$

  If $\sigma = E(T)\varepsilon_{elastic} > \sigma_y(T)$ → $\varepsilon_{elastic} = \varepsilon_{buckled\ beam} - \varepsilon_{plastic}$ → σ decreases

Elastic Modulus vs Temperature

- As Temperature increases the (E) decreases, due to the increasing distance between the ions of the metal lattice.
- Up to a temperature limit this effect is reversible
- At higher temperatures and often for sufficiently long permanence times the change can be irreversible: phase change, precipitations ... These effects are generally outside the testing range of vertical probes.

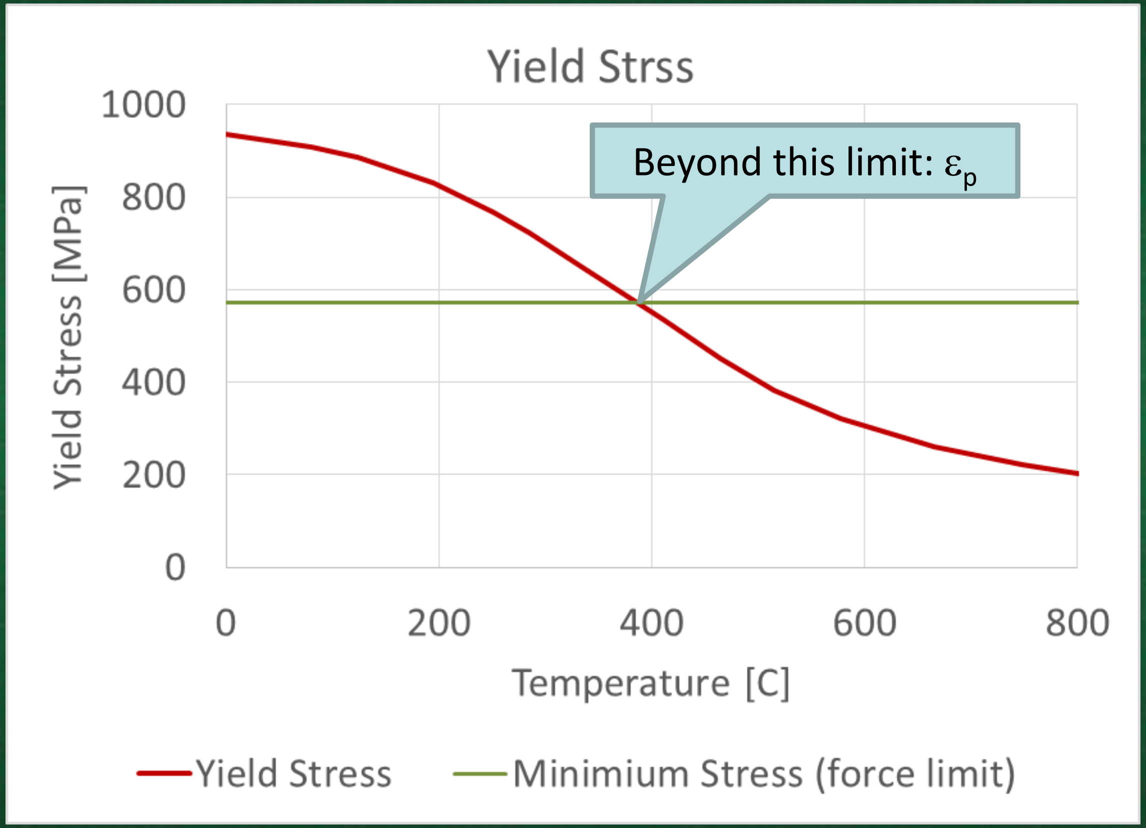


Yield Stress vs Temperature

- As temperature increases dislocation mobility increases, so the yield stress decreases, initially in a reversible way.
- If the stress in the probe exceeds σ_Y, part of the deformation ε becomes irreversible (ε_p), the elastic deformation decreases:

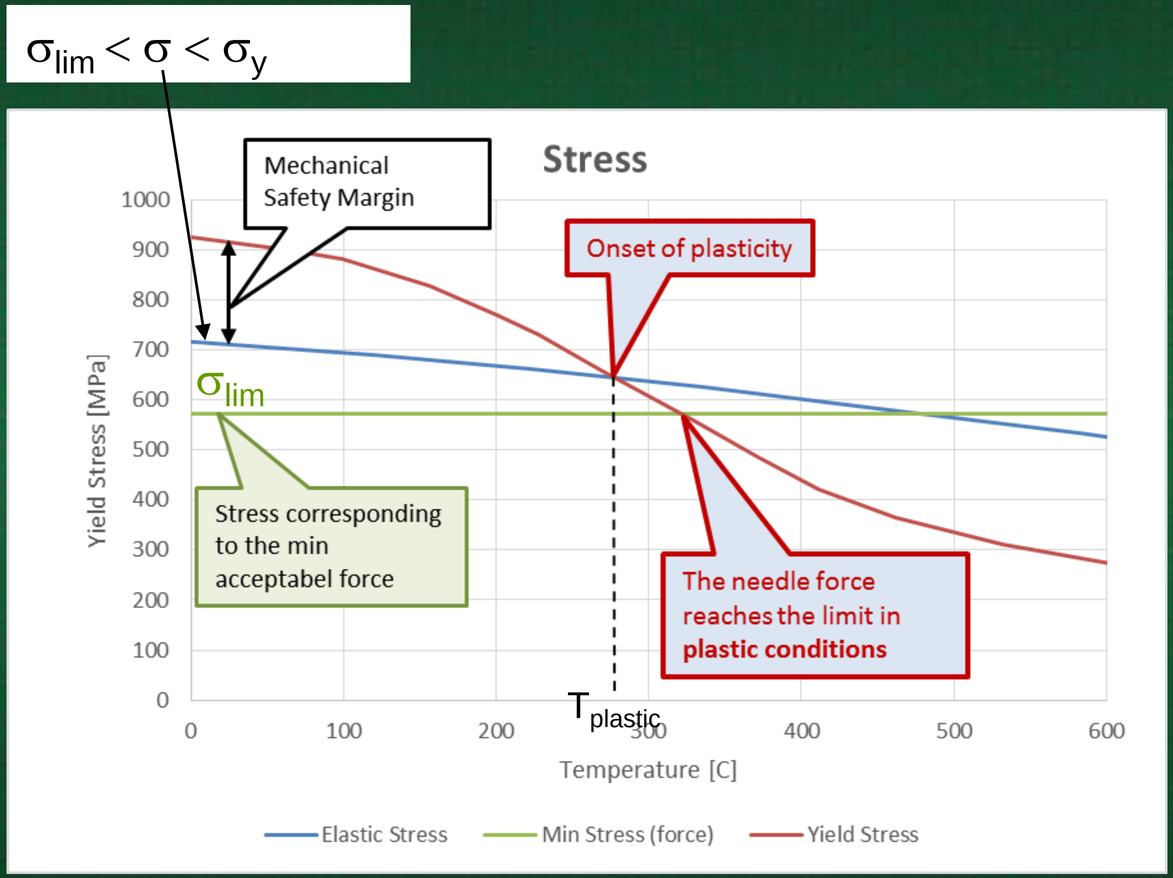
$$\varepsilon_{elastic} = \varepsilon_{buckling} - \varepsilon_{plastic} \,; \qquad \sigma = E(T)\varepsilon_{elastic}$$

and the stress decreases.
- At higher temperatures and often for sufficiently long permanence times σ_Y can undergo irreversible changes due to microstructural changes: grain growth, precipitation, solution, ... These effects are generally outside the testing range of vertical probes.



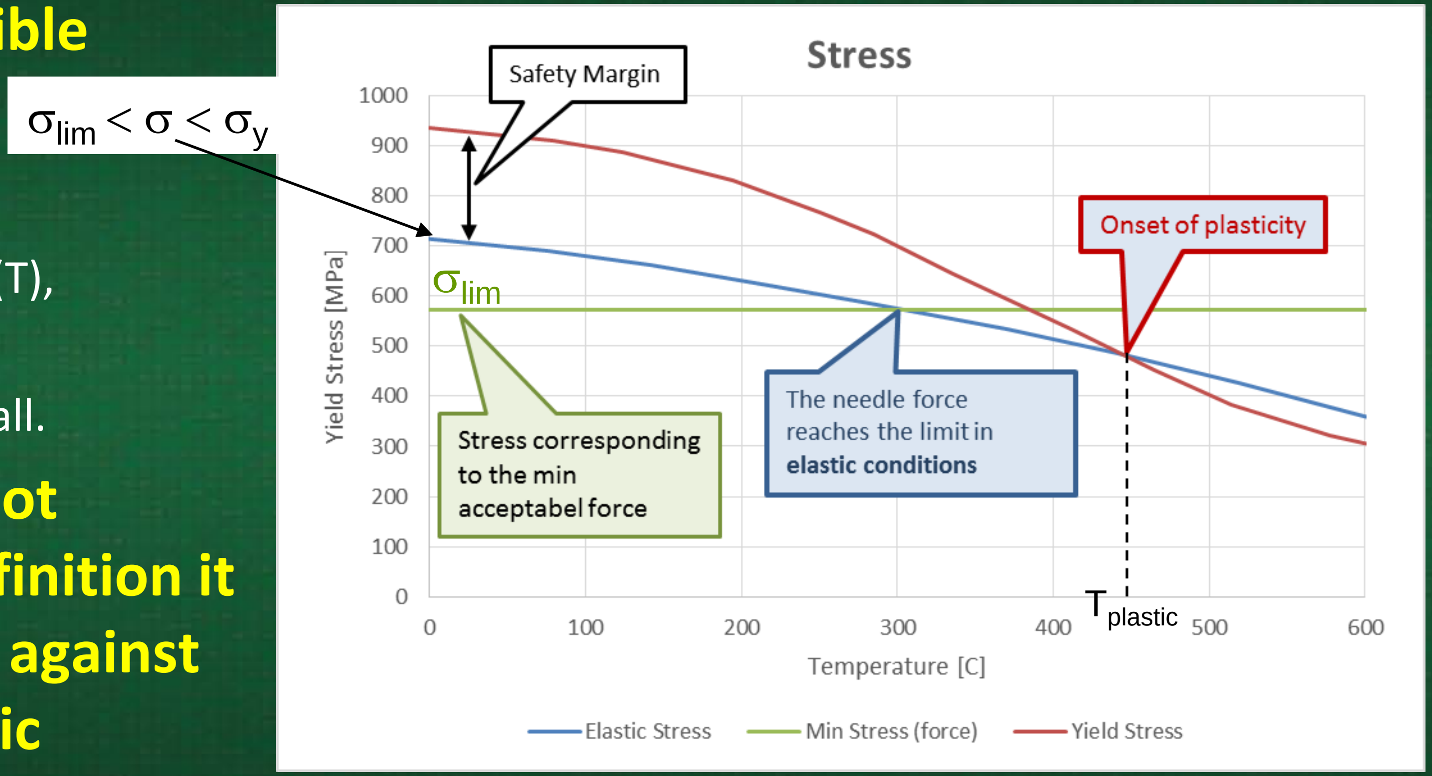
Putting All Together: Plastic Relaxation

- Let us assume a limit for the Force equal to a % of the initial force which ensures a good electrical contact: F_{lim}, which corresponds to a stress σ_{lim}
- When the temperature increases the stress due to the deformation of the buckled beam decreases; however the yield stress generally catches up because the drop in $\sigma_Y(T)$ is steeper than that of E(T).
- The temperature at which the two curves meet ($T_{plastic}$), defines the onset of plasticity.
- Before this temperature the force has already decreased due to the E(T).



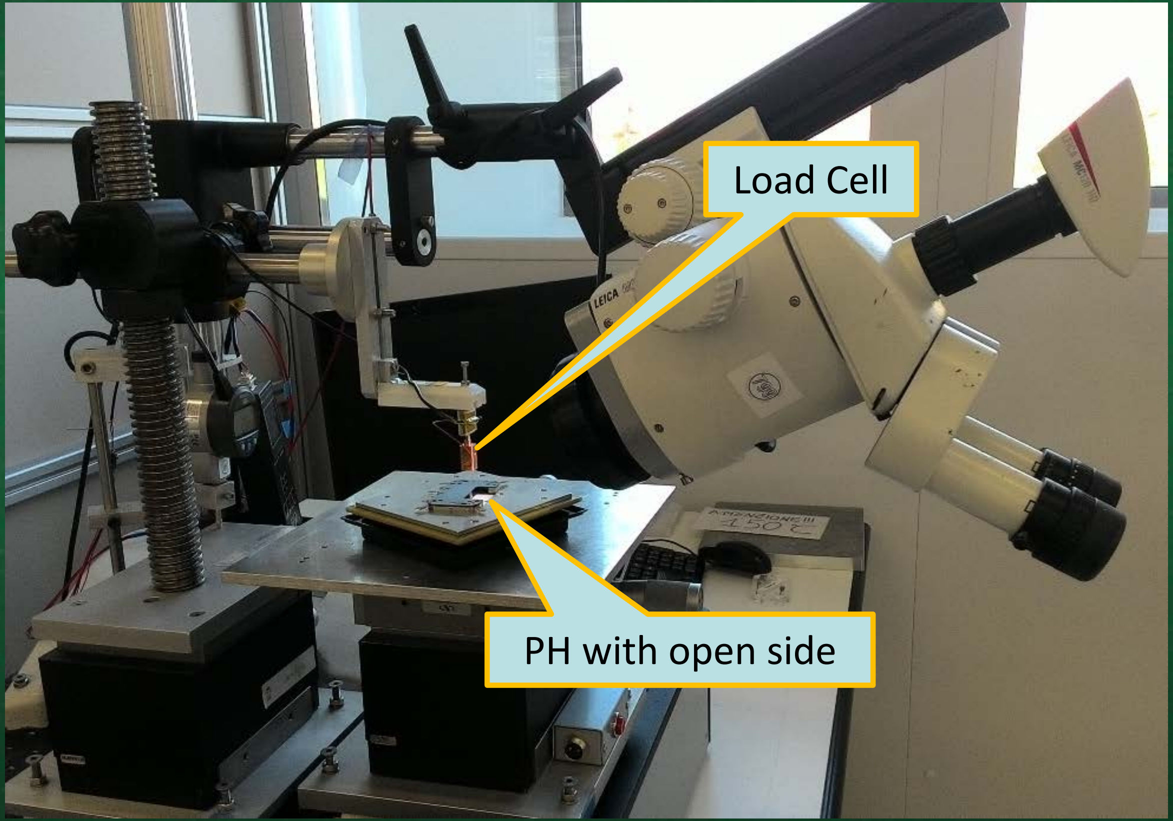
Putting All Together: Elastic Relaxation

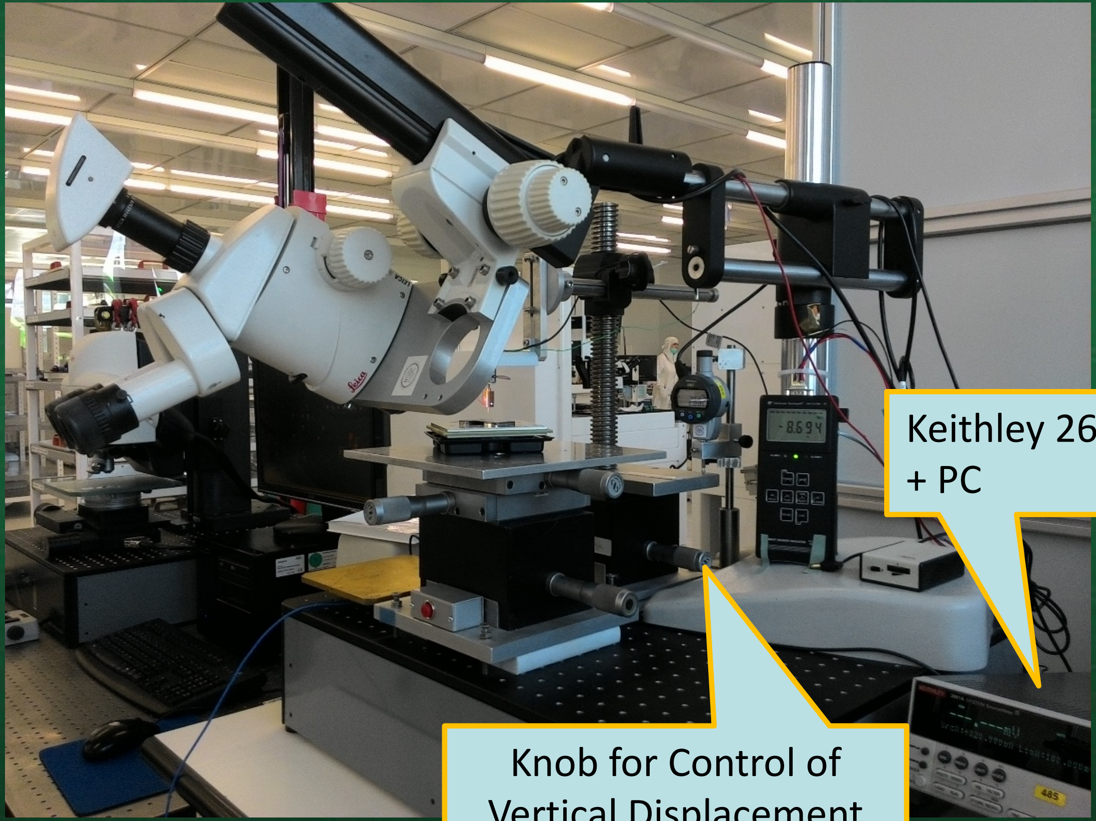
- **It is possible that F_{lim} is reached without plasticity, so still in a fully reversible condition**
- **This happens for example when:**
  - E(T) decreases "less rapidly" than $\sigma_Y(T)$,
  - The safety margin is "large",
  - The acceptable force decrease is small.
- **The ISMI2009 test procedure is not covering this case because by definition it checks the probe behaviour only against plastic relaxation. However elastic relaxation always precedes the onset of plasticity.**



Measurement Setup

- **The Measurement System is custom, and comprises a conductive load cell that allows continuous force measurements during cycling.**

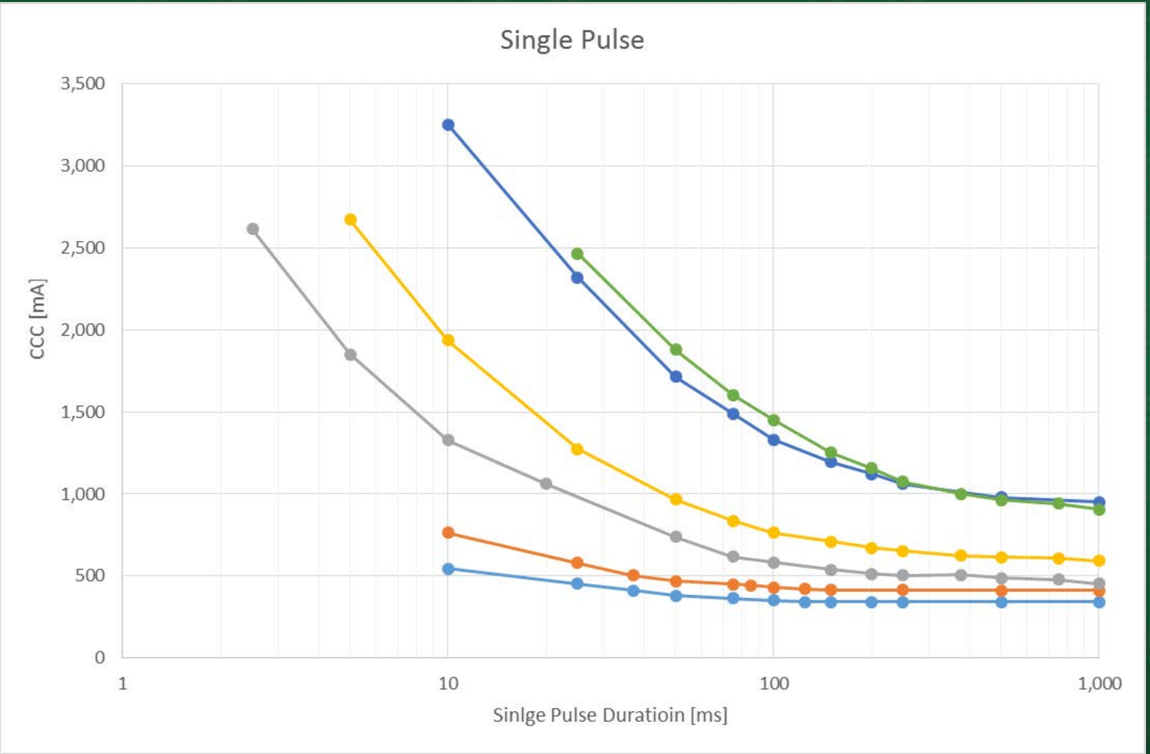




Dynamical Conditions: Single Pulse

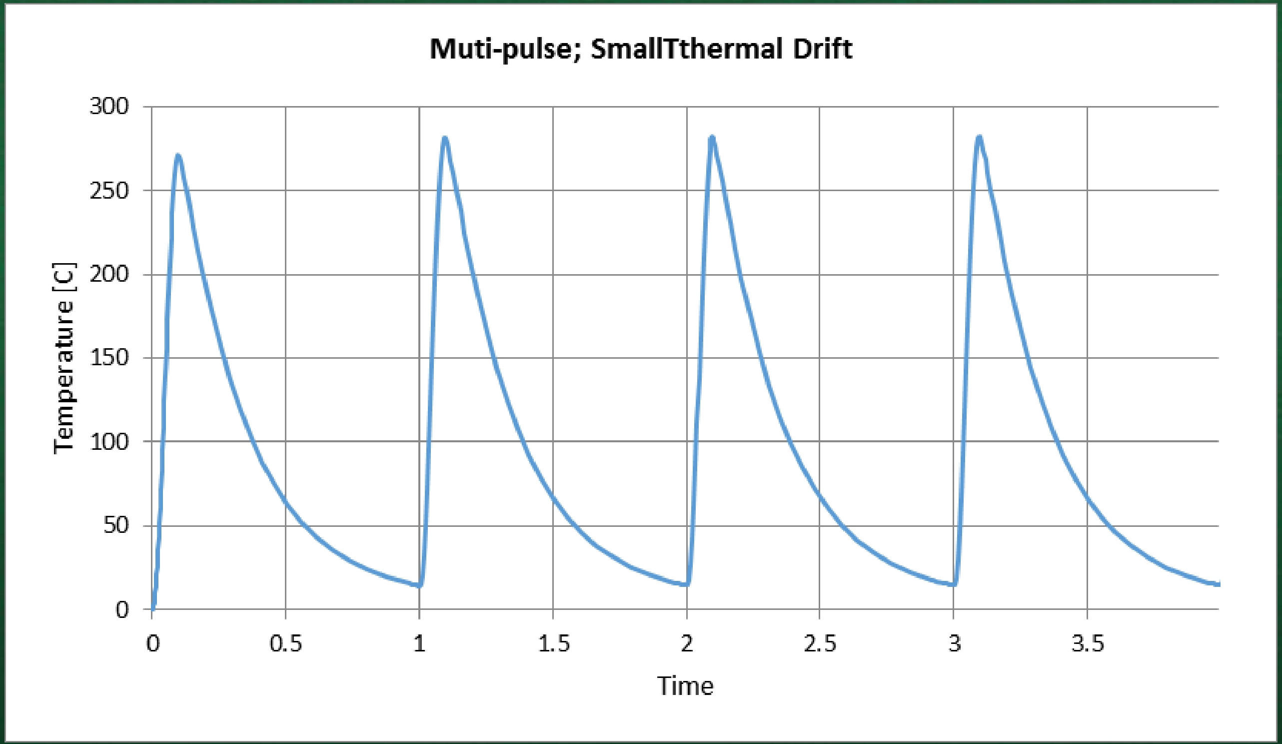
- In real test conditions the current is not constant and the balance between heating and cooling in the cycles is important.
- The simplest case of dynamical thermal condition is the single pulse: the probe has no time to dissipate the energy of the pulse.
- The graph on the right shows the results of single pulse on different probe types. As expected, the single pulse CCC decreases towards the DC CCC for increasingly long pulse durations.
- The characteristic time necessary to bring most of the probes at stationary conditions is about 100[ms].

CCC of Different Probes subject to a Single Current Pulse



Dynamical Conditions: Pulse Train

- If either the duty cycle (D), the on-time (on) or the current (I) are increased there will be some thermal drift.

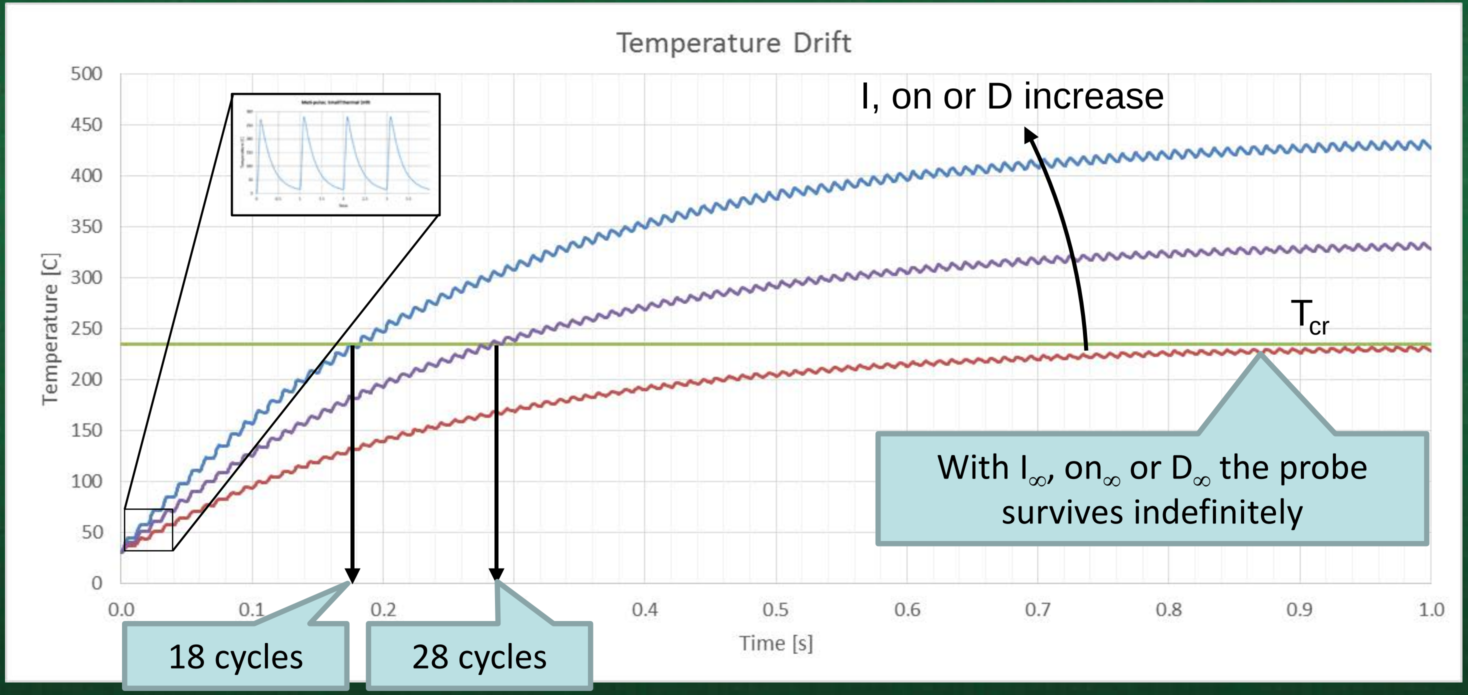


Thermal Drift

- If the cycles become short (cycle time shorter than the characteristic time) the temperature increase during cycling is determined by the thermal drift.

- T_{cr} is the temperature at which the force has decreased to the conventional limit.
- I_∞, $t_{on\infty}$ and D_∞ are the max values which allow an ∞ number of cycles.

Simulated Conditions

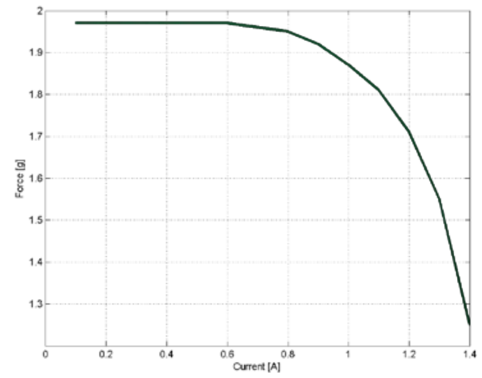


Pulsed CCC Measurement Sequence

The steps for ramping and measuring the CCC in pulsed conditions are as follows:

1. Measure the spring force of the probe at nominal overdrive.
2. Set the current source to 0.1 [A].
3. Apply pulse train made of Nx5 pulses with given duty-cycle (D) and t_{on},
4. Measure probe forces after a 30-second cooldown time.
5. Increment the current by 0.1 or 0.05 [A].
6. Repeat steps 3–5 until the force has dropped more than 50%.

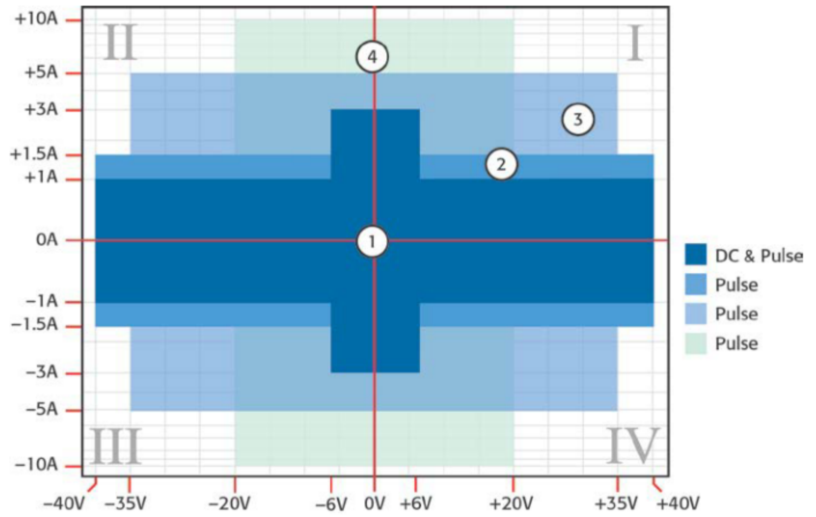
- The CCC value is obtained through an approximation of the data points with an analytic curve.
- The sample size should consists of three sets of 5 probes.



KEITHLEY
A Tektronix Company
Model 2601B

Minimum programmable pulse width[6] 100 µs

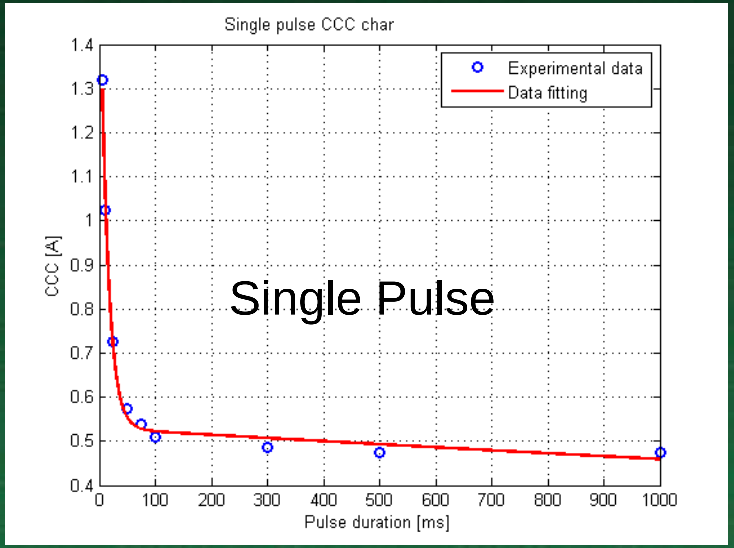
PULSE CHARACTERISTICS

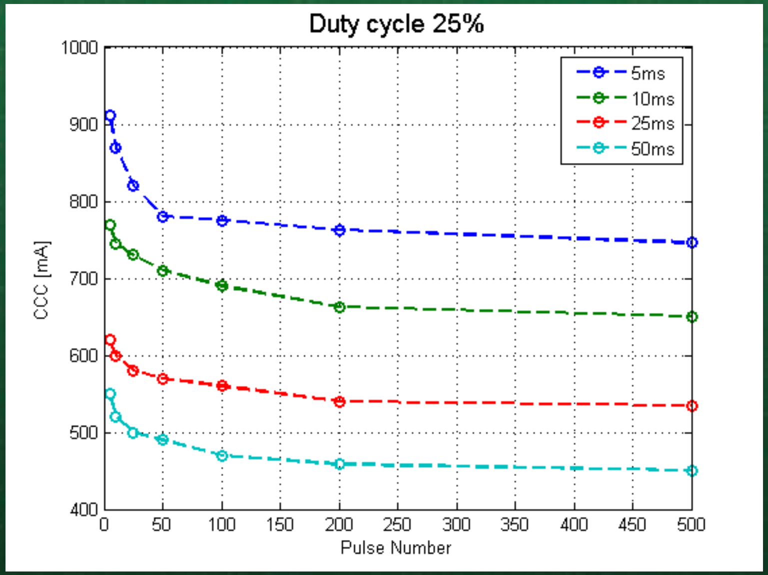


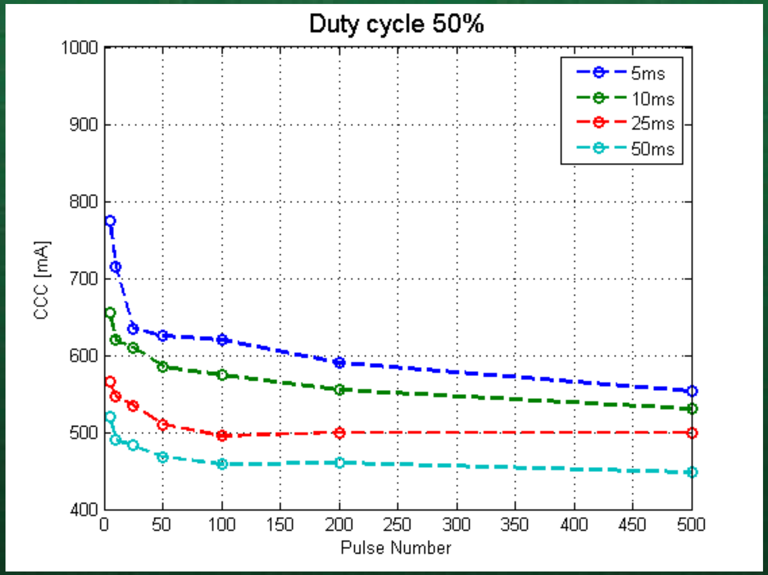
Pulse region specifications	Pulse region specifications			
	Region quadrant diagram	Region maximums	Maximum pulse width[6]	Maximum duty cycle[7]
	1	1 A at 40 V	DC, no limit	100 %
	1	3 A at 6 V	DC, no limit	100 %
	2	1.5 A at 40 V	100 ms	25 %
	3	5 A at 35 V	4 ms	4 %
	4	10 A at 20 V	1.8 ms	1 %

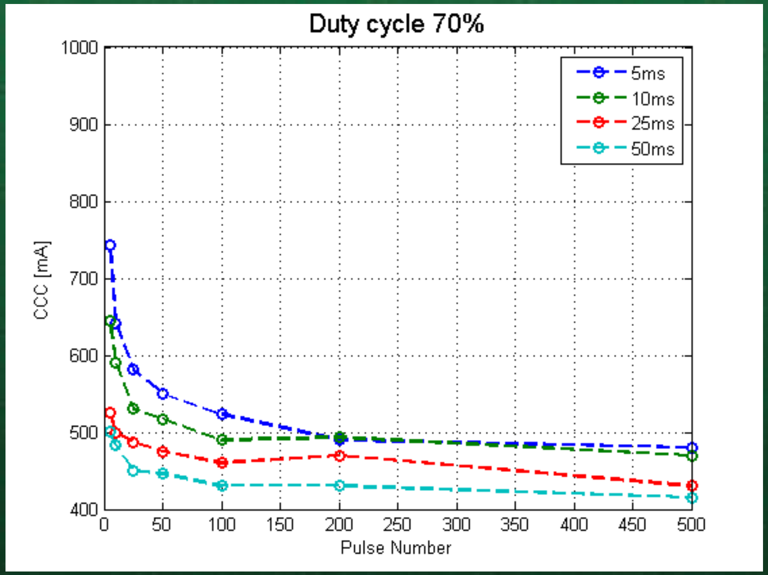
Experimental Results

- **As the duty cycle increases, the difference between the CCCs at different on-times shrinks. In fact the cycle becomes "similar" to a single pulse.**









Approximation and Numerical Model

- **In order to make the most of the experimental data there are two main ways:**
  1. **Approximation** of the data with analytical functions (or response surfaces). This would allow to:
     - predict CCC for conditions inside the envelop of the test matrix. (Fritting phenomena are not considered in this work)
     - Reduce the number of experiments necessary to characterize a probe of a specific material in test conditions, because the general trend of the CCC is known,
  2. Fit the experimental data with a **Numerical Model of the needle physics** (Finite Elements or other numerical methods).
     This would theoretically allow to:
     - Predict the CCC for any given complex cycling sequence,
     - If the convection coefficient and the contact resistance are known, it would be possible to predict the CCC for those specific conditions, like when the probes are in dense arrays.

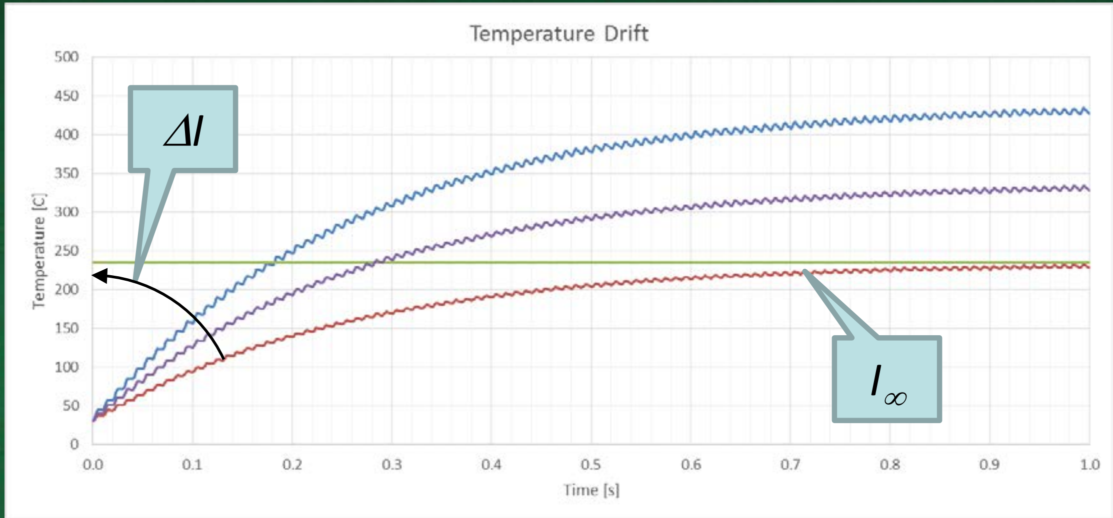
Approximation of Experimental Results

- For given cycling parameters (on-time, D) the CCC depends on current and number of cycles in a relatively straightforward way:

  $CCC = I_{\infty} + \Delta I\ f(N)$

  where:

  - I_{∞} *is the current which allows an infinite number of cycles,*
  - ΔI is the additional current to reach the single pulse limit.
  - *N* is the number of cycles,
  - *f(N)* is a function which must be 1 at 1 cycle and must decrease to 0 as N increases.



  – Experimentally: $f(N)= N^{-\tau}$ therefore: $CCC = I_{\infty} + \Delta I\ N^{-\tau}$

- I_{∞}, ΔI and τ can be interpolated for different D and on-times, and depend on:
  – Material,
  – Needle shape,
  – Convection conditions,
  – Contact resistance.

Example of Fitted Parameters: Single Pulse

- **The single pulse CCC(t_{on}) can be fitted through the same type of equation valid for Pulse Trains:**

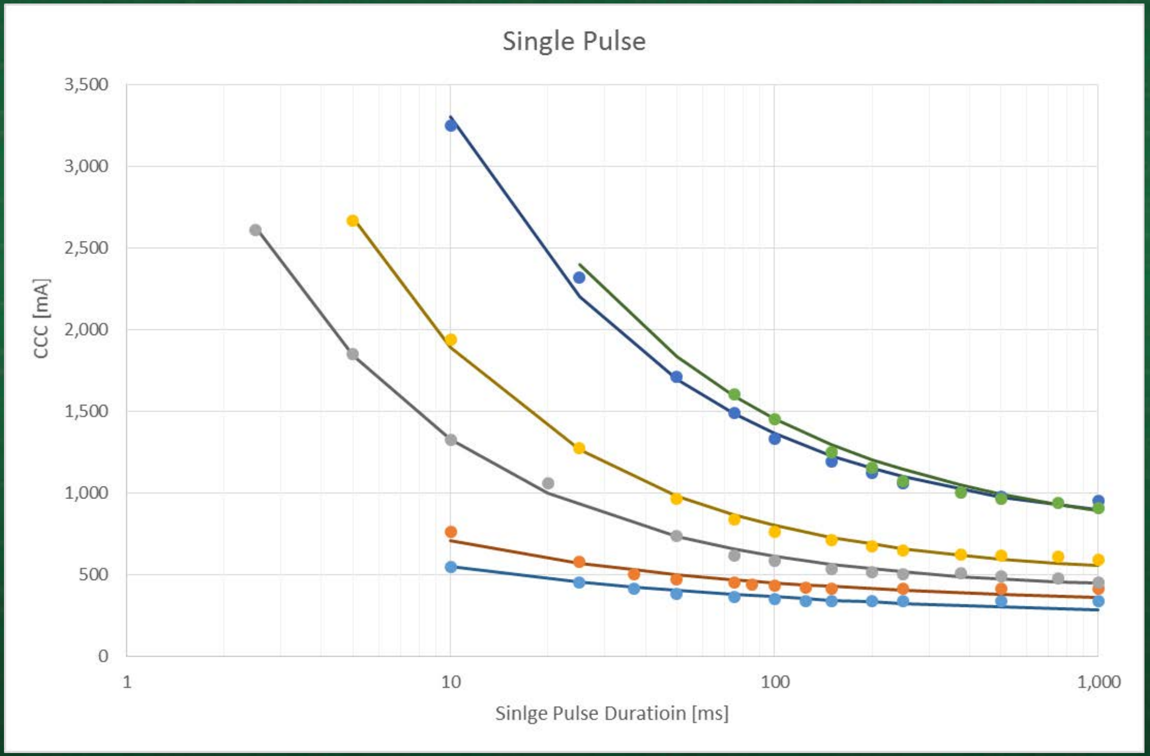
$$CCC_{single\ pulse} = CCC_{DC} + \Delta I_s\, t_{on}^{-\eta}$$

where:

- CCC_{DC} is the DC CCC,
- *ΔI_s is the additional current theoretically corresponding to a 1 [ms] pulse duration,*
- *t_{on} is the on-time,*
- *η is a fitting constant.*

- **The fit is quite good.**

Continuous lines show the fitted curves



Example of Fitted Parameters: Pulse Train

Continuous lines show the fitted curves

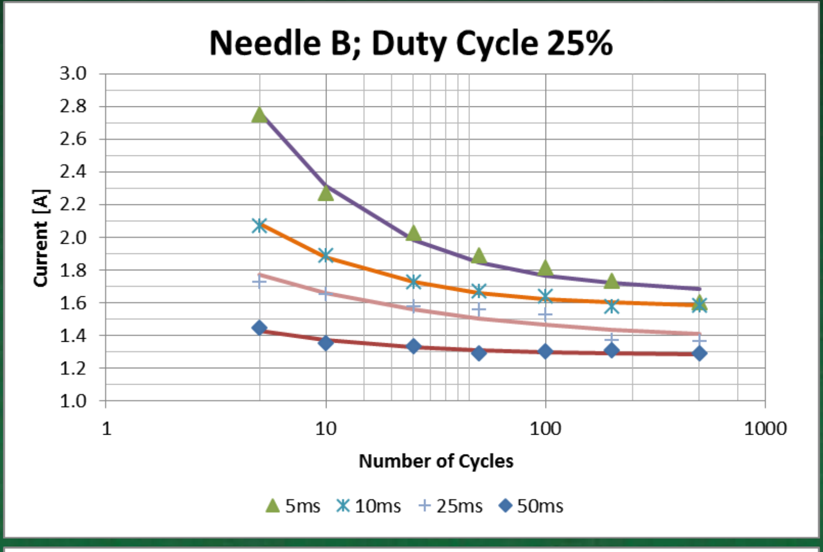
- **Approximation:**

$$CCC = I_{\infty} + \Delta I \; N^{-\tau}$$

Duty Cycle 25%					
on-Time ms	5	10	25	50	Unit
I_{∞}	1.649	1.569	1.357	1.284	A
ΔI	3.742	1.713	0.860	0.498	A
τ	0.752	0.745	0.453	0.759	

Duty Cycle 50%					
on-Time ms	5	10	25	50	Unit
I_{∞}	1.110	1.196	1.162		A
ΔI	4.691	2.164	0.828		A
τ	0.783	0.813	0.758		

Duty Cycle 75%					
on-Time ms	5	10	25	50	Unit
I_{∞}	0.948	0.993	0.991	0.910	A
ΔI	4.551	2.901	1.481	0.615	A
τ	0.753	0.821	0.796	0.619	

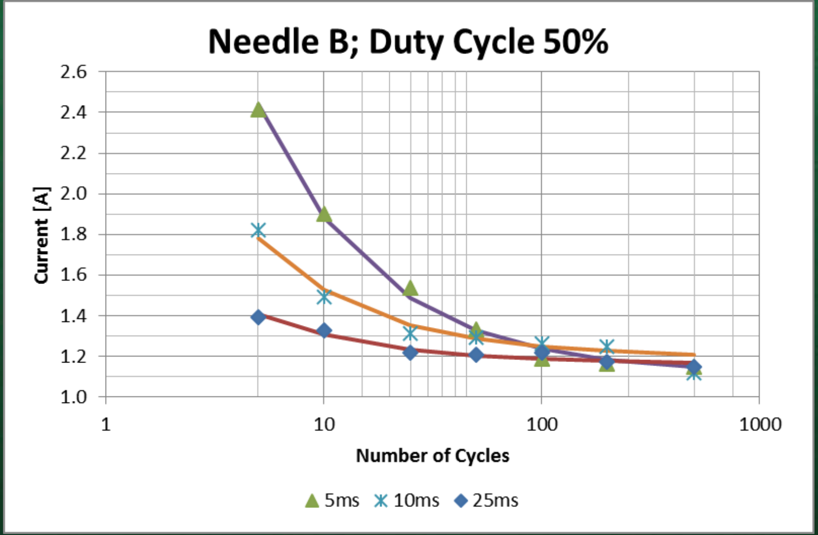


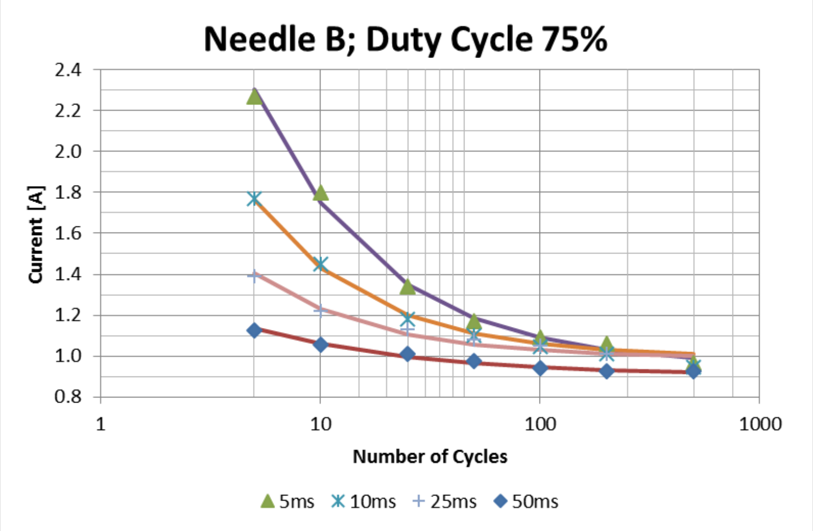
An example:

$$\begin{cases} I_{\infty} = -1.214E\text{-}03\ t_{on} + 0.9878 \\ \Delta I = 19.485\ t_{on}^{-0.8504} \\ \tau\ -3.632E\text{-}03\ t_{on} + 0.8290 \end{cases}$$

where:

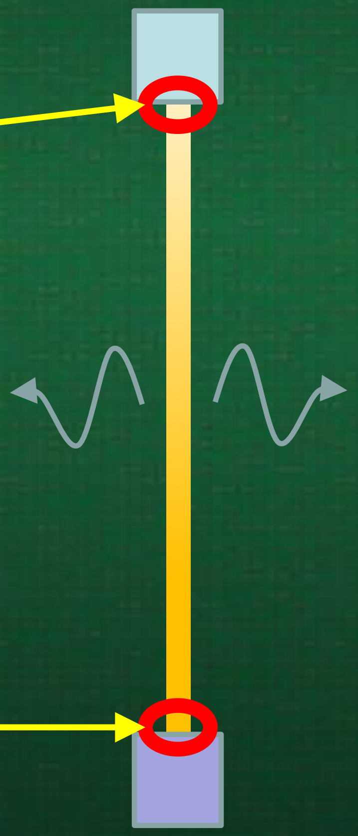
- t_{on} is the on-time in [ms]
- I is the current in [A]





A Possible Way Forward: Numerical Simulation

- **The probe can be simulated with a thermal Finite Element (FE) Model (other numerical techniques would be suitable as well).**
- **The model should consider:**
  - Convection on the probe sides ($q=h\Delta T$),
  - Contact resistance (superficial heat source)
  - Ohmic resistance (volumetric heat source) ($P=IR^2$)
- **For the relatively low T of vertical probes, radiation plays almost no role**



Towards a Realistic Prediction

- **As the ISMI2009 explains, real convection conditions can differ from those of the test setup.**
- **The most important parameters of the real test environment to be known for a realistic prediction are:**
  - contact resistivity,
  - convection conditions: coefficient (h) and fluid temperature (ΔT); $q = h\Delta T$
- **The contact resistivity often varies significantly during testing, but its value is generally limited by design requirements.**
- **Convection conditions can be estimated through non-dimensional formulas or through CFD simulations.**

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ISMI Probe Council Current Carrying Capability Measurement

3.5 Extensions

While the guideline addresses a simple DC application of current on a single wire at ambient temperature, the production environment is likely quite different. Multiple wires, tests at high or low temperature, pulsing current supplies, and different interface materials and metallurgy are just a few conditions that will cause the wire to have a different CCC during production. Any of these conditions, and many others, may lead to a derating of the standard CCC for most production applications.

Conclusions

- **Increasingly more demanding CCC requirements push towards more sophisticated assessment methodologies and a precisely defined dynamic thermo-mechanical responses.**
- **The ISMI2009 test procedure is not covering elastic relaxation despite the fact that elastic relaxation always precedes the onset of plasticity.**
- **The most basic way to define a dynamical CCC is through a measurement in simple test conditions:**
  - Single Pulse tests,
  - Pulse Train tests.
- **We performed a series of CCC test in both conditions.**
- **The trends were approximated analytically, allowing the interpolation of any untested condition.**

Next Steps

- We are considering a way define a CCC which takes into account the elastic relaxation of the probes and not only the plastic relaxation.

- It is possible to envisage a numerical simulation of the dynamical conditions, which, after validation, would allow to evaluate any sequence of pulses and different convection conditions, more similar to the real tester environment.