Continuous Current Conduction and Long Term Performance of Bare and Coated Contacts at High Temperatures

Lecture

IEEE switchgear meeting 2016-04-28

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Contents

- Basics of current conduction across contacts and connections
- Design rules for contacts and connections built of different materials
- Ageing mechanisms
- Temperature rise and ageing tests
- Behavior of connections with different coatings

Reference IEC/TR 60943: 2009 Technical committee 32: fuses

Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals.

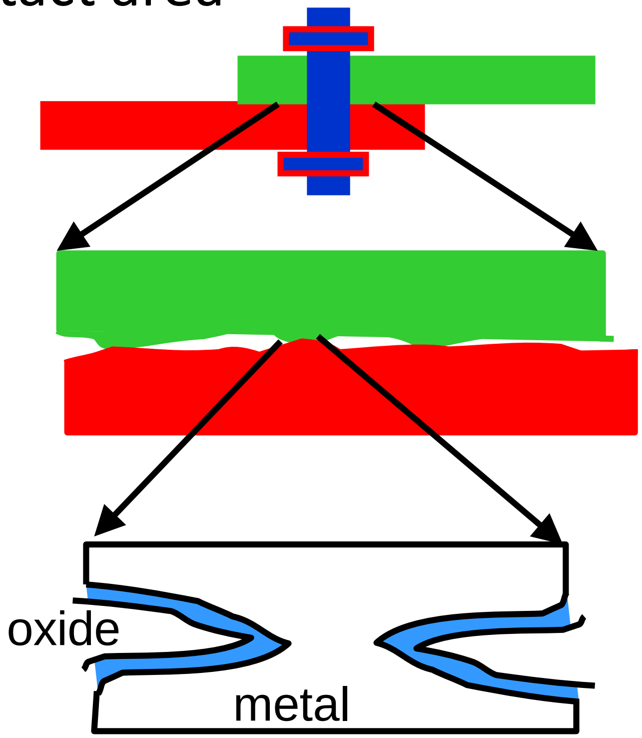
- The report is intended to supply:
  - general data on the structure of electric contacts and the calculation of their ohmic resistance;
  - the basic ageing mechanisms of contacts;
  - the calculation of the temperature rise of contacts;
  - the maximum “permissible” temperature and temperature rise for various components;
  - the general procedure to be followed by product committees for specifying the permissible temperature and temperature rise.

Definitions

1. Fixed contacts = connections
   - Bolted connections
   - Connections not intended to be removed
2. Movable contacts
   - Sliding or rolling contacts
   - Contacts for disconnecting purposes
   - Contacts for switching purposes
   - Touching contacts in vacuum
   - Sliding contacts in gases

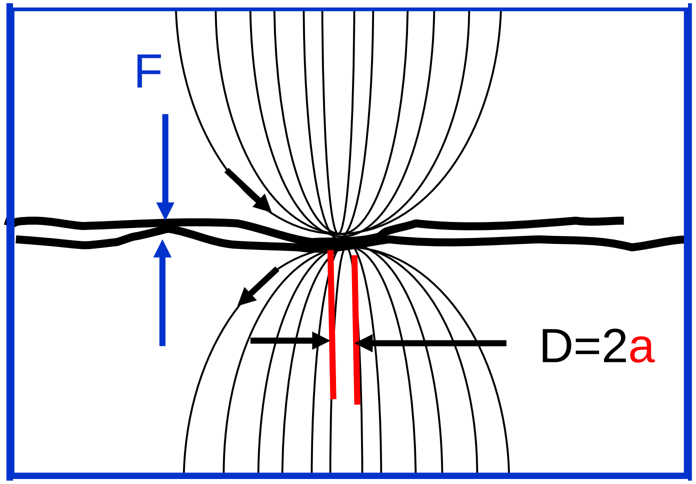
Current flow across bolted connections

- Real contact area
  - is smaller than the apparent contact area
  - Due to micro roughness
  - Due to oxide layers
- Real area is depending on
  - Clamping force
  - Hardness of material
  - Cleanliness of surface
  - Number of contact points



Real contact area

- The material deforms at the contact point in accordance to its yield strength σ_y until balance is achieved between plastic deformation force ($A \cdot \sigma_y$) and contact force F
- A is the real contact area



$$A = \pi a^2 = \frac{F}{\xi \sigma_y}$$

- Yield strength can be determined from the hardness of the material:

  Brinell Hardness HB or Vickers Hardness HV.

- HB is the diameter of the indentation of a metal ball on the surface (CuCr 75/25: HV=82, HB=78, σ_y =261 N/mm²)

Contact resistance

- The contact resistance is calculated from the specific resistivity and the contact radius

$$R_E = \frac{\rho_{el}}{2a} = 0{,}89\,\rho_{el}\sqrt{\frac{\xi\sigma_y}{F}}$$

- ρ_{el}: spec. resistivity
- a: radius of contact point
- F: contact force
- ξ : flatness factor 0.3 – 0.6
- σ_y : yield strength in N/mm²

- In additon, the film resistance of the surface layer (oxide etc) should be considered.
  - Mostly, oxide layers are thin (< 10 nm) and conduction is due to electron tunneling

- σ_0: Tunnel resistivity

- The contribution of the film resistance is negligible even for Al-oxides unless the contact forces are small (< 100N)

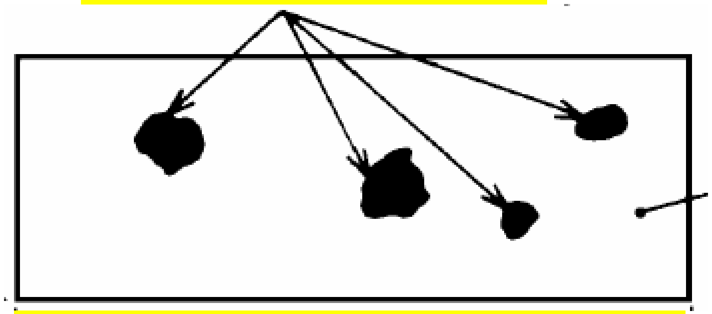
$$R_I = \frac{\sigma_0}{\pi a^2}$$

Impact of several contact points on the resistance

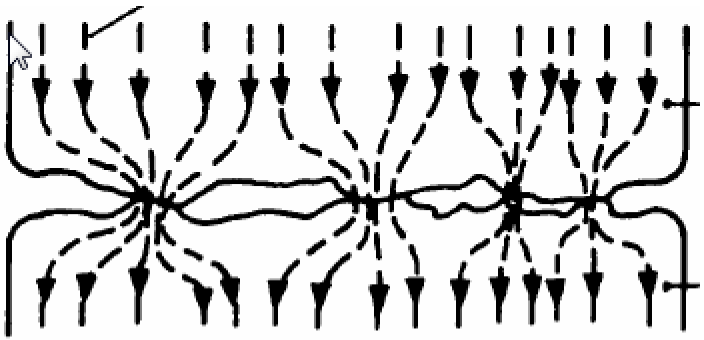
- n parallel contact points give lower total resistance

$$\pi a_n^2 = \frac{1}{n} \pi a_1^2 \quad \Longrightarrow \quad R_E = \frac{1}{n} 0{,}89 \rho_{el} \sqrt{\frac{\xi \sigma_y}{F/n}}$$

Real contact points



Apparent contact area



Contact heating

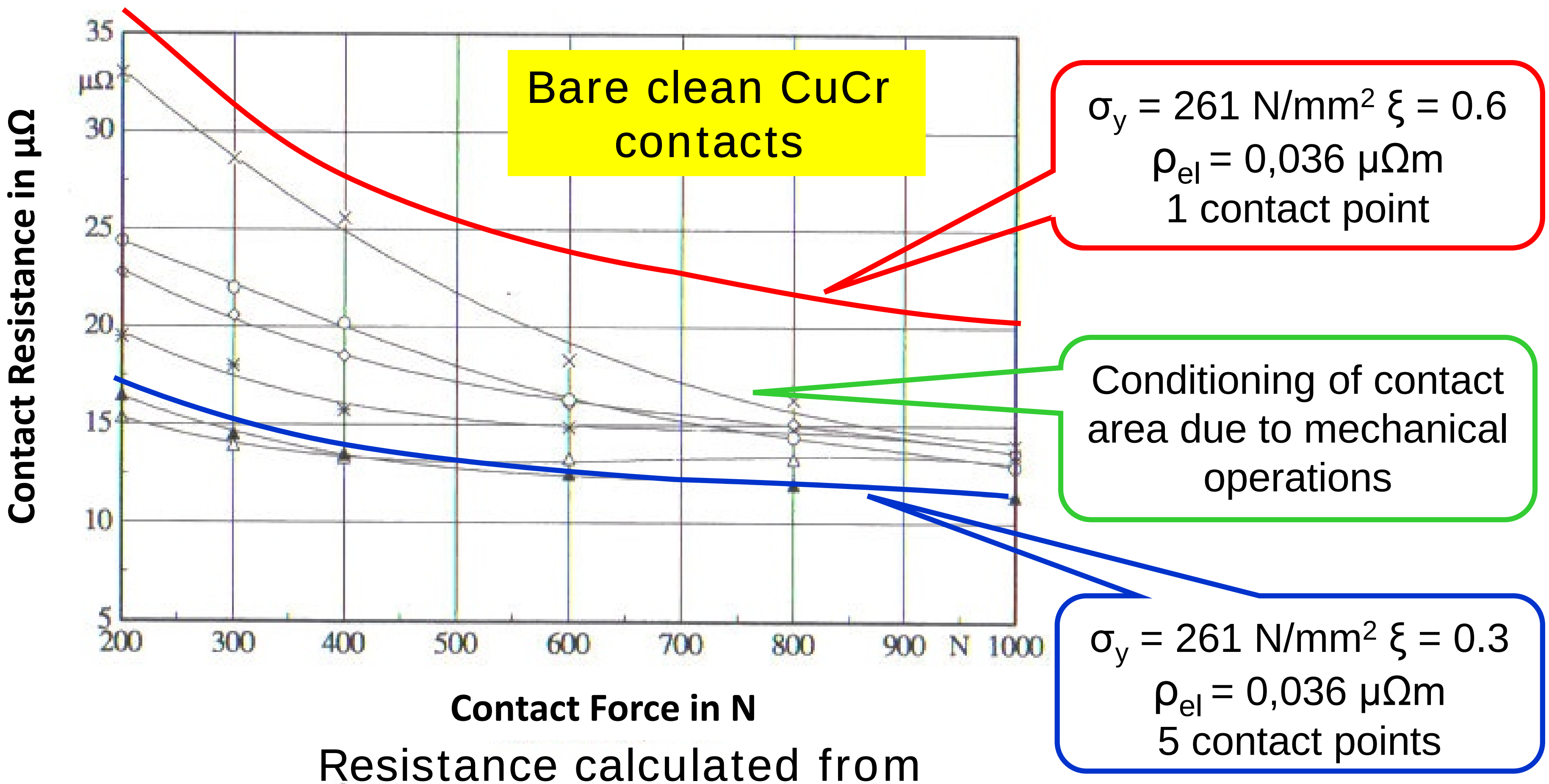
- Heating of the contact points

$$\Delta T = \frac{1}{\sqrt{\pi\lambda\rho c}} \frac{P_{el}}{\pi a^2} \sqrt{t}$$

- T: contact temperature
- λρc: material parameters
- P_{el}: ohmic power loss
- t: duration of current flow

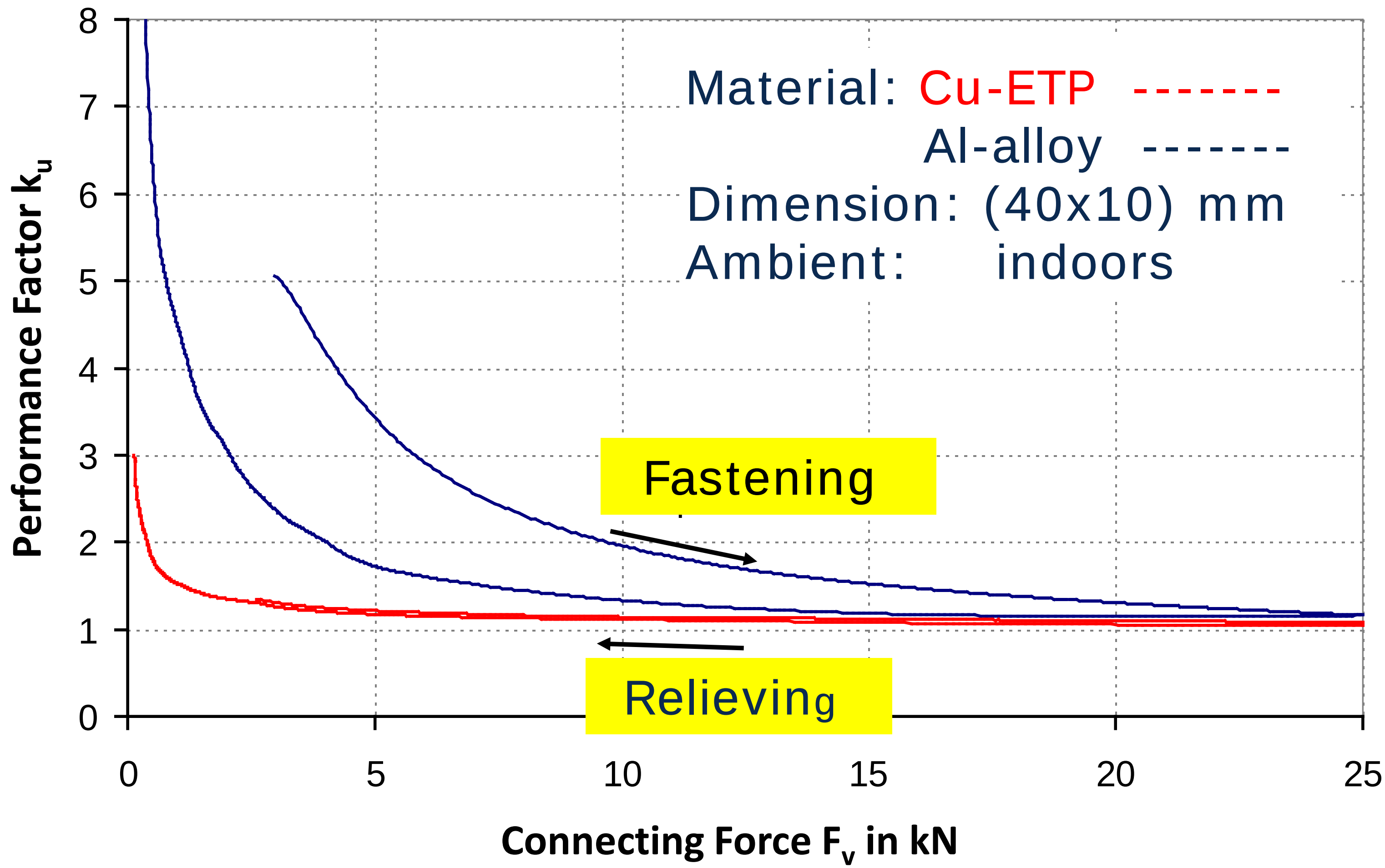
- Examples:
  - Continuous current 1000A and 2500N
    gives between 19 and 33K temperature rise after 10s
  - This formula cannot be applied for such long times
    since heat conduction through the leads in not considered.
  - Short time curent of 25 kA and 2500N
    gives between 3800 and 6500K after 1 s.
  - This only is an indication that the melting temperature
    will be probably exceeded and welding might occur.

Resistance as function of force for a vacuum interrupter



Resistance calculated from formula including a constant resistance of leads of 8 μΩ

Hysteresis between resistance and force for bolted connections

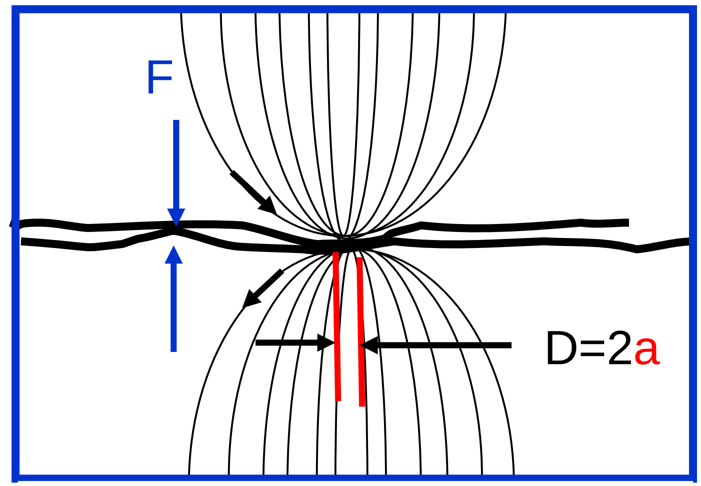


Constriction forces

- Repulsion of closed contacts due to the electro-dynamic forces of current constriction

$$F_R = \frac{\mu_0}{4\pi} i^2 \ln\left(\frac{\pi \cdot r}{2a}\right)$$

  - E.g. 5130 N for a peak current of 125 kA with r/a = 17



- F_R: repulsion force in N
- μ_0: induction constant
- r: apparent electrode radius
- a: radius of contact point

with n contact points

$$\Rightarrow \quad F_R = \frac{\mu_0}{4\pi} \frac{1}{n} i^2 \ln\left(\frac{\pi \cdot r}{2a_n}\right)$$

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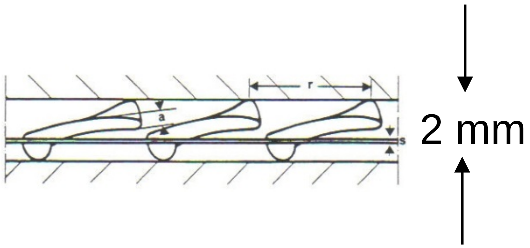
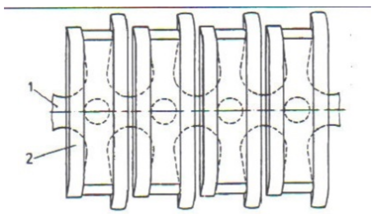
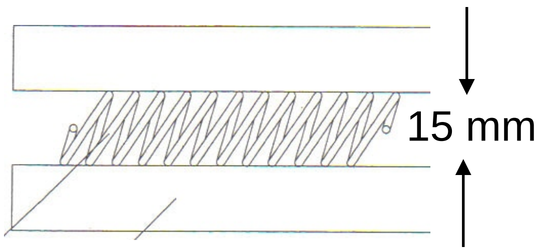
- Ageing mechanisms
- Temperature rise and ageing tests
- Behavior of connections with different coatings

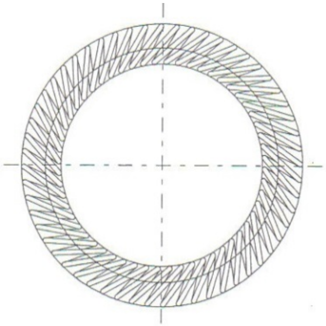
Design of movable contacts

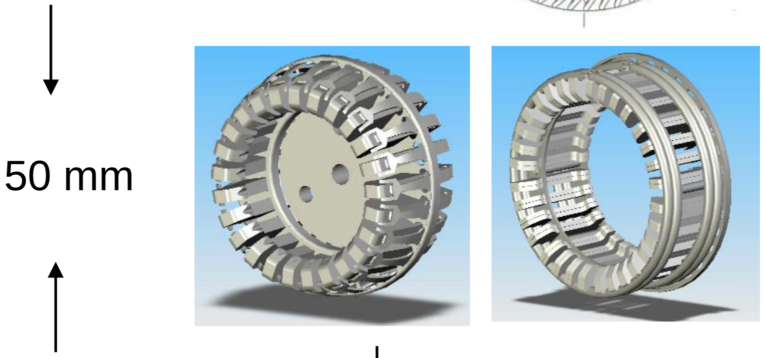
- Multi-contact bands
  - Steel blade springs (band)
  - Single Ag-plated copper elements
  - Special groove
- Spiral contact spring
  - Endless spring, Ag plated
  - Cu-Beryllium or Cu–Circonium
  - Simple groove
- Finger contacts
  - Circumferential tension springs
  - or single blade springs
  - Massive Ag-plated Cu fingers
- Flexible copper bands
  - Multiple Cu-bands each 100 µm
  - Ag plated terminals possible

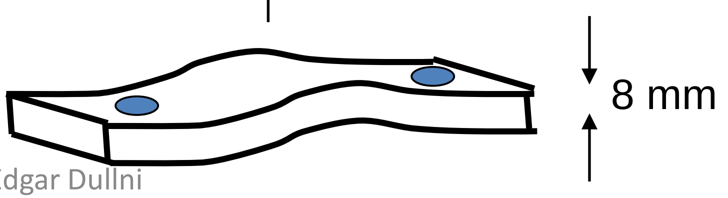












Comparison of aluminum and copper

	Al	**Cu**
Resistivity in μΩ cm	2,86	1,76
Yield strength in N/mm² (from hardness)	220 – 350 up to 800 for alloys	450 – 950 < 100 annealed
Oxidation	immediate oxidation in air, thick layer	Some oxidation (black, red)
Surface preparation	Critical, thorough brushing required	brushing recommended
Stress relaxation	Critical, within days to years	Not critical
Ageing	Can be quite fast	Stable
Corrosion protection	Silver with Cu undercoat	Silver plating

Design criteria

- Do not combine different materials in one connection (e.g. Ag with Al, or Al with Cu)
- Exert an appropriate contact force by using spring washers
  - To ensure the required low resistance and therefore low heating under continuous current
  - To avoid increase of resistance due to material relaxation and plastic deformation
- When using threaded holes in Al or Cu, either apply special inserts or cold formed threads.
- Apply coatings to improve the electrical properties and longevity of the connection.

Coatings (Ag)

- Undercoat by 10 µm of Cu or Ni needed for Al and Al-alloys
- 3 µm of Ag-coating is sufficient for fixed connections and indoor ambient conditions
- 20 µm of Ag-coating is necessary for sliding contacts and exposed outdoor ambient conditions
- Passivation by chromium compounds is possible in order to prevent tarnishing in air, Cr VI in Europe needs authorization!

• ASTM International: B700 – 08 – Standard Specification for Electro-deposited Coatings of Silver for Engineering Use

• DIN EN ISO 4521:2008 – Metallic and other inorganic coatings — Electrodeposited silver and silver alloy coatings for engineering purposes

Coatings (Ni)

- Plating with Nickel
  - Wear resistance is good because of high hardness
  - Used also for outdoor conditions because of good corrosion resistance
  - Higher contact resistance because of higher film resistivity

Fastening, general rules

- Use nuts and bolts with corrosion protection e.g. Zinc chromate (without Cr VI) in quality class 8.8
- When using stainless steel bolts because of exposed outdoor conditions be aware of the reduced tensile strength (class only 4.6 or 5.6)
- Use appropriate spring washers – and plane washers – to compensate for material stress relaxation (Al) or different elongation under temperature variations.
- Prescribe the correct contact forces (see table 1) using the correct fastening torques of bolts (see table 2)
- Use more bolts and a larger apparent contact area for higher currents
- Clean surface from oxides before assembly (important for Al)

Fastening forces and torques

- The minimum values of force related to the continuous rated current for static connections are:
- The tightening torques for steel bolts class 8.8 without grease are:
- With grease on bolts the tightening torques are much smaller, forces are equivalent.

2016-03-21

Aluminum	60 N/A
Copper	40 N/A
Ag and Sn coat	40 N/A
Ni coat	50 N/A

	torque	force
M12	86 Nm	39600 N
M10	50 Nm	27100 N
M8	26 Nm	17000 N

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- **Ageing mechanisms**
- Temperature rise and ageing tests
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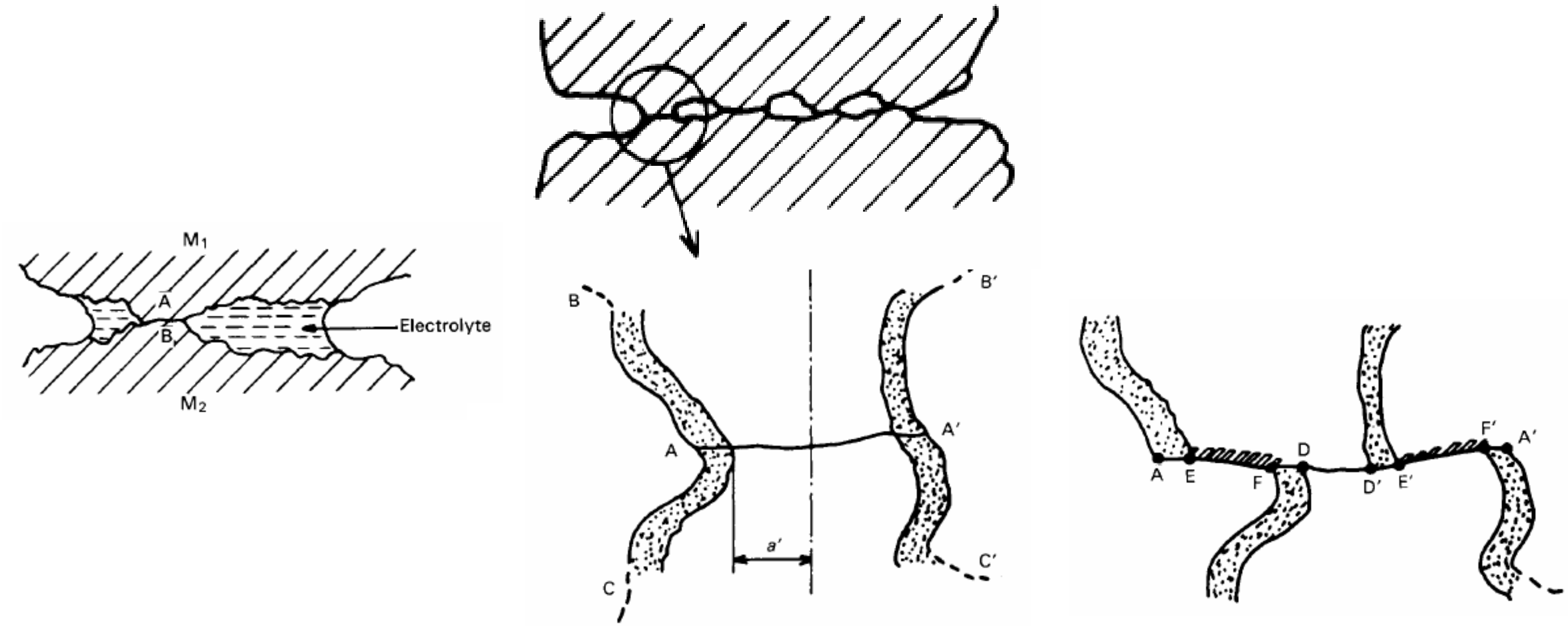
Ageing mechanisms

1. Chemical reactions
2. Fretting wear
3. Force reduction
4. Interdiffusion
5. Electro migration

Chemical reactions /corrosion

- Chemical reactions:
  - Formation of highly resistive oxide layers or other compound layers dimishing the area of contact points
  - Galvanic corrosion of bi-metal connections (electrolyte)
  - Reduction of the real contact area and increase of contact resistance
  - In particular under severe climates in industrial areas, high humidity, salty atmosphere
  - Micro-movements of surface oxides accelerate ageing on electrically closed contacts, not on bolted connections due to much higher contact forces.

Chemical reactions /corrosion from IEC/TR 60943: 2009

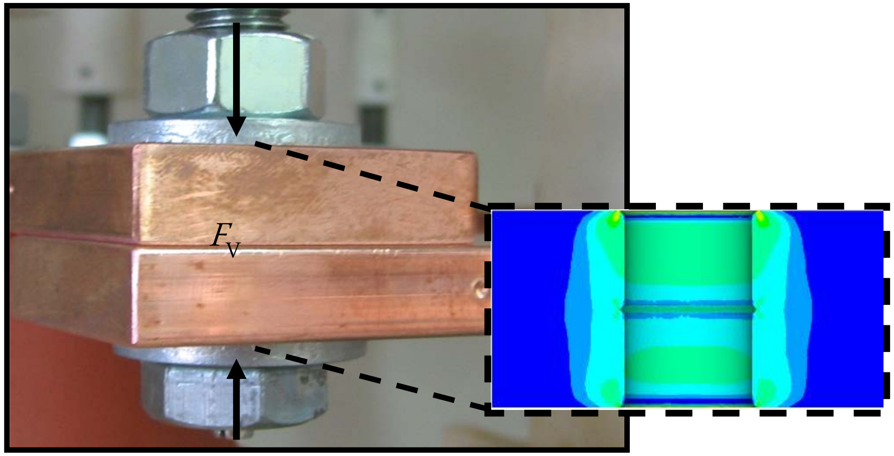


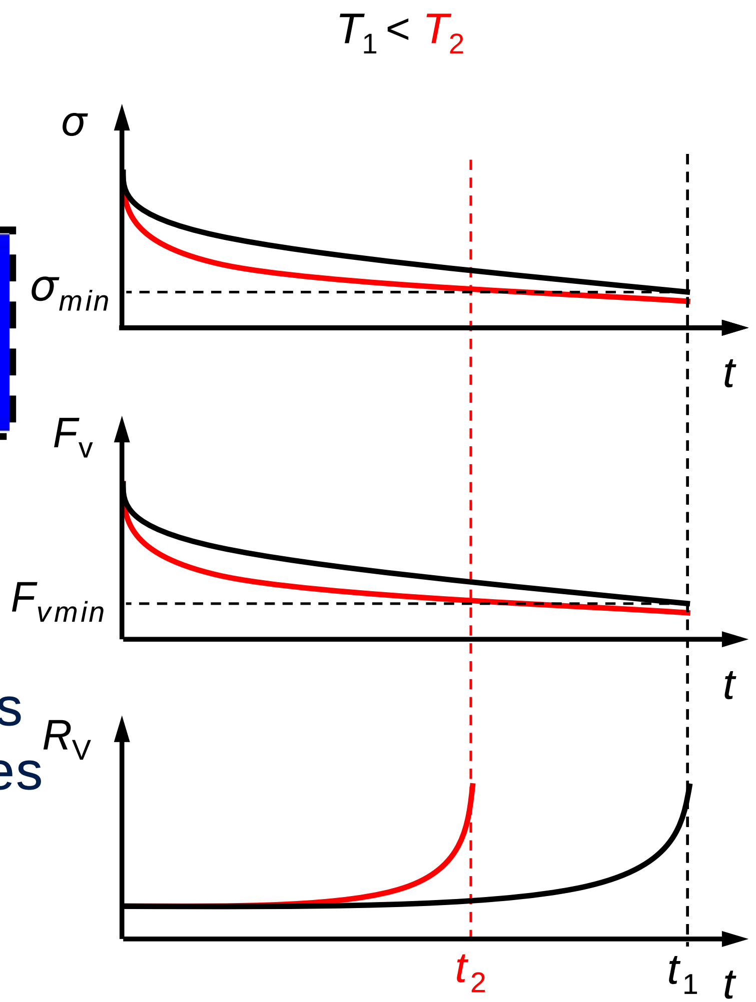
- Contacts subjected to current cycles deteriorate more quickly than those carrying a constant current. These cycles result in differential thermal expansion at the contact area which leads to micro-movements of the faces in contact with each other.

Fretting wear / Force reduction

- <u>Fretting wear</u>
  - Wear of coatings due to abrasion with relative movements
  - Wear particles migrate between contacts and increase resistance
  - Depending on material combination, but in particular for tin-coated contacts
- <u>Force reduction</u>
  - Reduction of the connecting force due to relaxation of material stress, in particular for bolted connections
  - setting process, dynamic recovery, recrystallisation and grain coarsening
  - Depends on tensile strength of material, which can be increased by cold forming

Contact force reduction by material relaxation



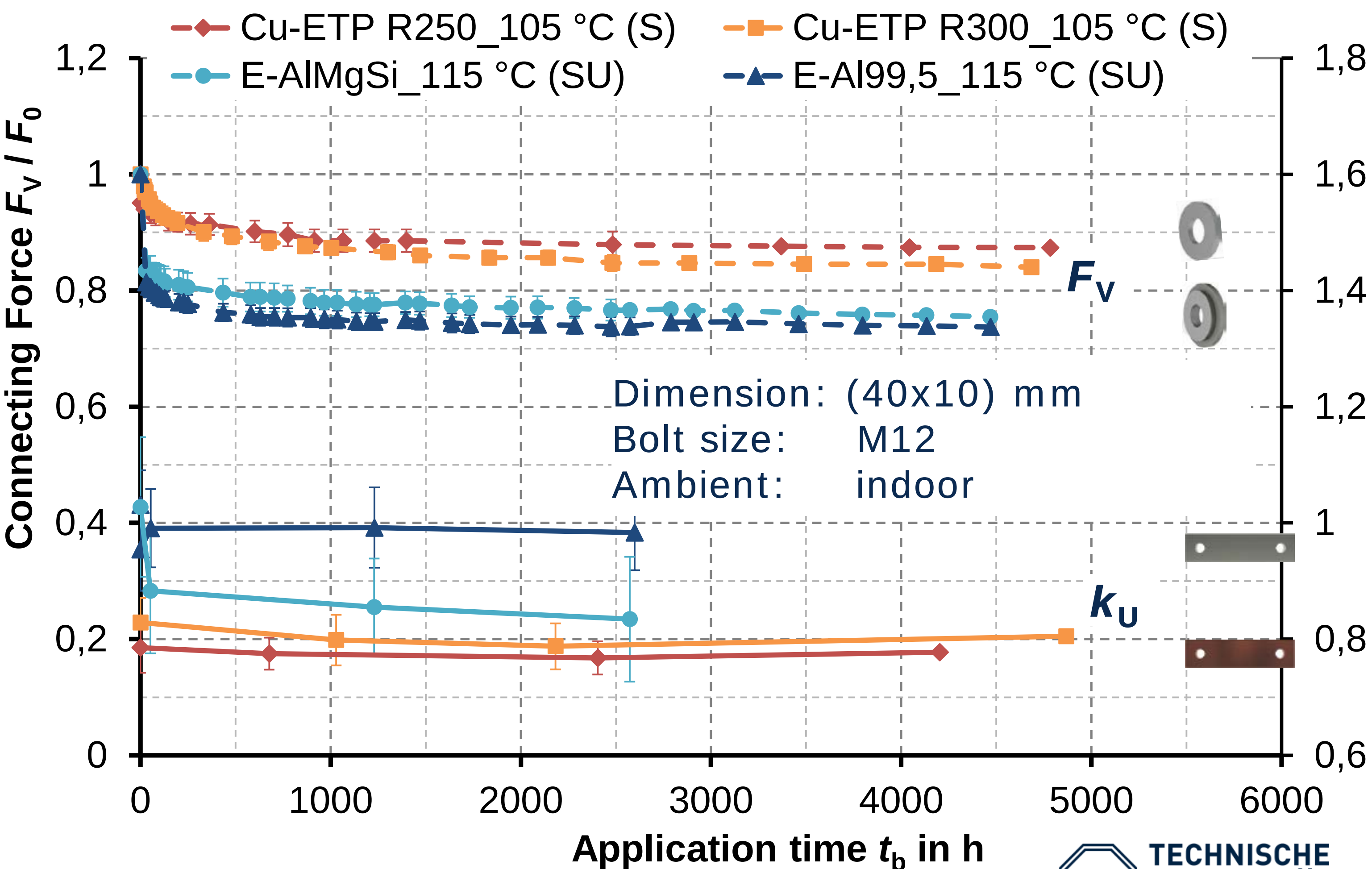


- Bolting of connections
→ exerts a mechanical force

- Relaxation of the mechanical stress through different physical processes in dependence of temperature, material and time.

→ Reduction of the contact force

Contact force reduction by material relaxation



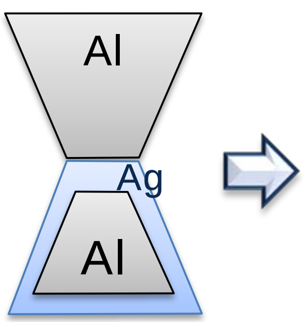
Intermetallic processes

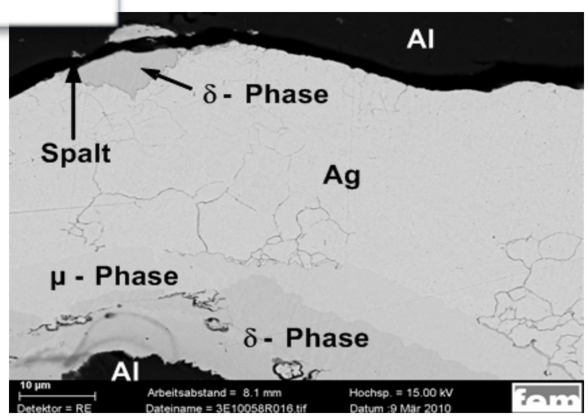
- <u>Interdiffusion</u>
  - Formation of an intermetallic phase with different electrical and mechanical properties
  - High resistance of intermetallic phase
  - Depending on material combination
- <u>Electro migration</u>
  - Material transport under high current density and current gradients
  - Formation of micro voids
  - Diffusion of impurities and grain boundaries
  - In particular for direct current applications, but also for high alternating currents

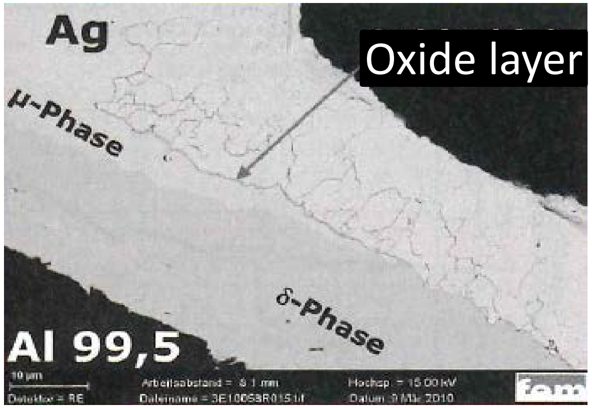
Diffusion between Al and Ag

Microscopic examination of one point of contact between a silver-coated and a bare aluminum bus bar with a grooved contact surface

Property	Al	Ag	Intermetallic compounds	
			δ - Phase (Ag_2Al)	μ - Phase (Ag_3Al)
κ_{IMP} in MS/m	**36**	**62,9**	**2,9-3,1**	**1,7-1,9**
$\alpha_{T\ IMP}$ in $\cdot 10^{-3}$ K^{-1}	4	4,3	0,93-0,94	0,55-0,66
***H* in HV**	**58**	**72**	**203**	**488**







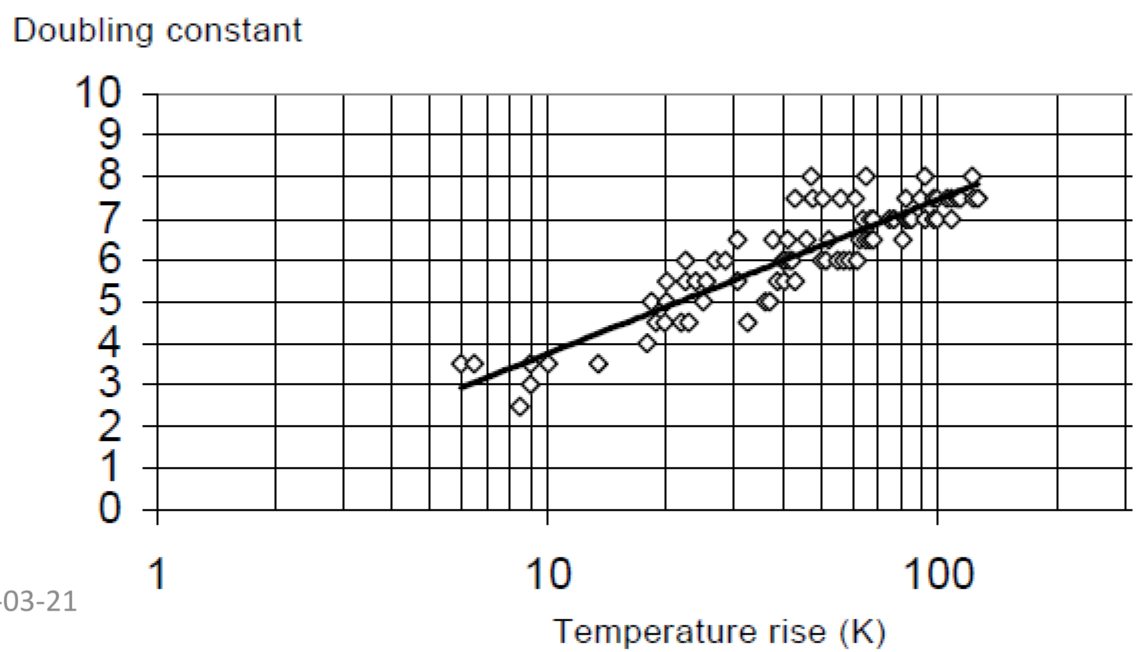
1. Interdiffusion in the bi-metal Al-Ag
2. Oxygen diffusion through the Ag-layer

Ageing of fixed connections in air depends on

- Initial contact resistance
  - Ageing is faster, if the resistance is higher for the same assembly
- Contact material
  - No oxidation for Ag or Sn coated contacts, little oxidation for bare Cu and Ni, but high oxidation for bare Al
- Contact force
  - Reduction is faster with smaller force especially for Al due to stress relaxation
- Surface treatment
  - Grease only retards ageing, is necessary for sliding contacts
- Current flow
  - High contact temperatures accelerate ageing
- Ambient conditions
  - Fast ageing can occur in humid and SO_2 containing air

Impact of temperature on ageing from IEC/TR 60943: 2009

- Chemical reactions, oxidation, force relaxation, growing of intermetallic phases and diffusion are determined by temperature
- The Arrhenius law describes this dependence.
- When the temperature rise of a contact increases from a value ΔT_{i1} to a value ΔT_{i2}, life is multiplied by an ageing factor K_i which is expressed as function of the doubling constant Δ_i



$$K_i = 2^x$$

$$x = \frac{\Delta T_{i1} - \Delta T_{i2}}{\Delta_i}$$

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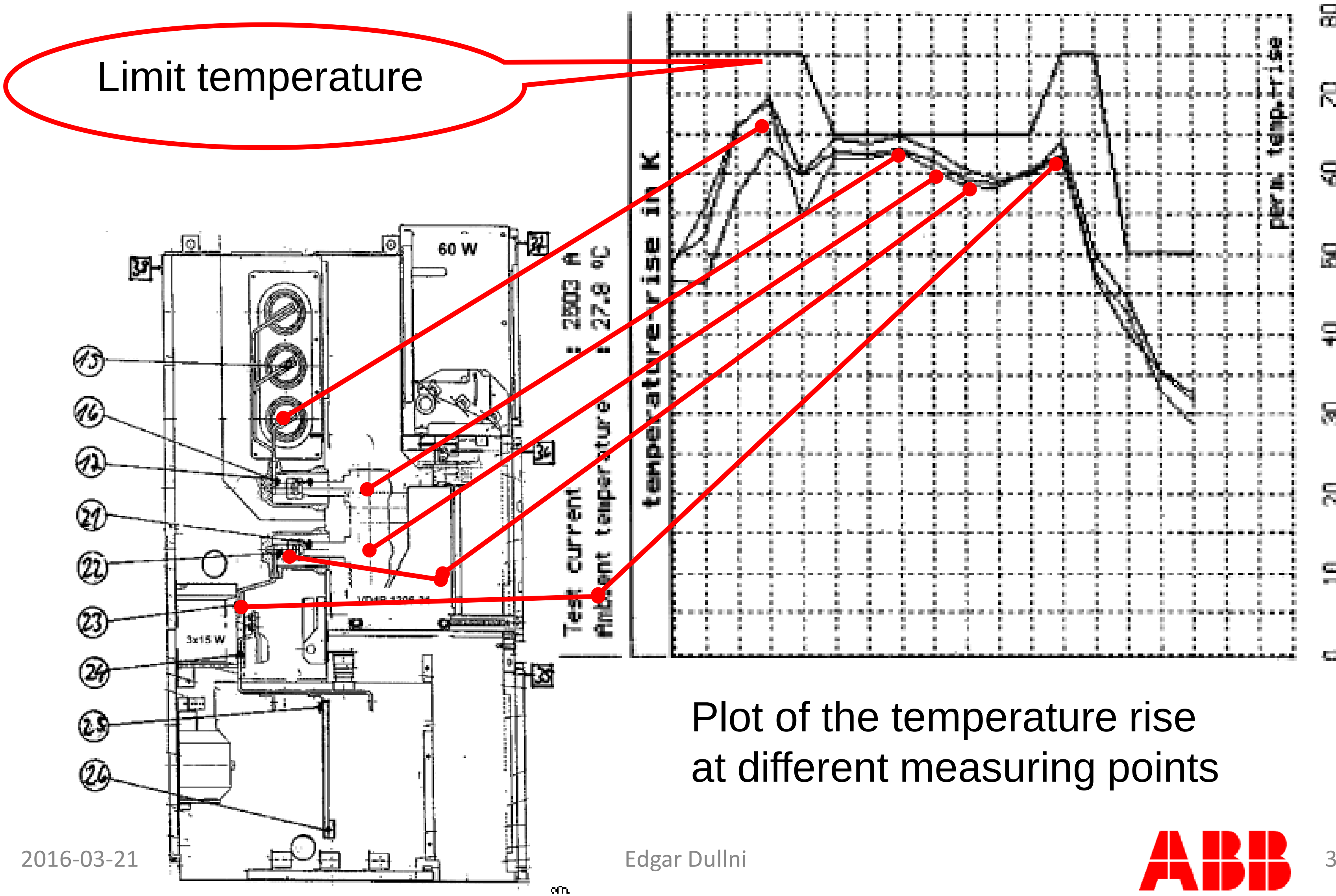
Temperature rise type tests

- Test is done at rated continuous current
- The temperature of all relevant and accessible points is measured by thermo couples
- The measured temperatures must not exceed the limit temperatures permitted by ANSI IEEE standards (IEC 60943)
- The ambient temperature is maximum 40°C (for higher temperatures rated current may be reduced)
- The test is stopped when the temperature rise is < 1K in 1 h
- For the recalculation of temperature and currents within a small range, one can use (determined for Cu-bars):

$$T_{total} = T_{amb} + \Delta T \qquad \frac{I}{I_{meas}} = \sqrt[1.67]{\frac{\Delta T}{\Delta T_{meas}}}$$

Temperature rise test in a switchgear assembly



Plot of the temperature rise at different measuring points

Limit temperatures in Table 6 from IEC/TR 60943: 2009

- Column A: components susceptible to ageing, but whose rapid destruction temperature is high.
- Column B: components whose temperature must not exceed a certain value, otherwise very rapid destruction will occur.

Description of component		Column A Maximum temperature rise K[u] (θ_{an} = 20 °C)	Column B Maximum temperature °C (θ_{an} = 40 °C)	Remarks
Spring contacts	Copper and copper alloys uncoated			
	– In OG[t]	35[p]		
	– In NOG[t]	75[q]		
	– In oil	40		
	Tinned in OG, NOG[t], oil[b e]	50		
	Silver-[b, s] or nickel-plated[b]			
	– In OG[t] or NOG[t]	75[q]		
	– In oil	50		
	For contactors, in oil		105	Deterioration of the oil
Bolted connections	Copper, aluminium, and their alloys, uncoated			
	– In OG[t]	60[q]		
	– In NOG[t]	75[q]		
	Tinned[b] in OG or NOG[t]		105	Creep point of tin
	Silver-[b, s] or nickel-plated[b]			
	– In OG or NOG[t]	75[q]		
	– In oil		100	Deterioration of the oil
	For contactors, in oil		105	Deterioration of the oil
Terminals[d, f, r]	To be connected to exterior conductors by screws or bolts			
	Uncoated	60[q]		
	Tinned[b]		105	Creep point of tin
	Silver- or nickel-plated[b]	75[q]		

Non-oxidizing gases

75K for silver plated contacts

Temperatures permitted in continuous current tests

Joints with differently coated contact partners or **one part is of bare material:**

IEC:
Higher temperature limit of coated material is permitted

ANSI IEEE:
Only lower temperature limit of uncoated material is permitted

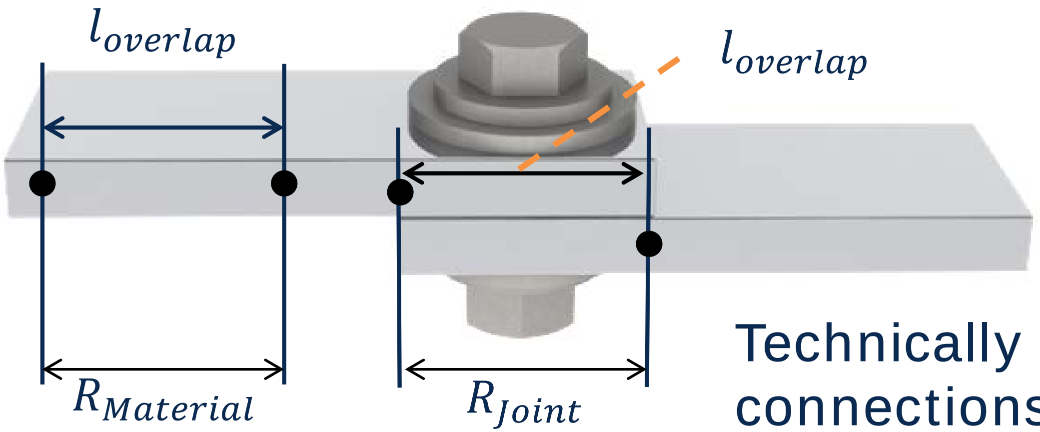
Internat. standard	**Temperature limit for connections in air (bolted or equivalent)**	
	Contact partner	Temperature limit
IEC 62271-1:2007/A1:2011	Bare copper, copper alloy or aluminum alloy	90 °C
	Sn-coated	105 °C
	Ag- or Ni-coated	115 °C
ANSI IEEE C37.100.1:2007	Bare copper, copper alloy or aluminum alloy	90 °C
	Sn-coated	105 °C
	Ag- or Ni-coated	115 °C

Publications

- Fuhrmann, T. et al. – „Comparison between nickel and silver as coating materials of conductors made of copper or aluminum used electric power engineering, 27th ICEC, 2014
- Fuhrmann, T.; Schlegel, S. et al. – „Investigations on stationary electrical joints with a bare and a silver or nickel coated contact partner regarding the permissible temperature limit according to ANSI IEEE and IEC, 60th IEEE Holm Conference on Electrical Contacts, 2014
- Schlegel, S. – "Langzeitverhalten von Schraubenverbindungen mit Stromschienen aus Reinkupfer in der Elektroenergietechnik unter besonderer Berücksichtigung der Temperatur", PhD thesis, TU Dresden, 2011
- S. Schlegel, S. Großmann, H. Löbl, M. Hoidis, U. Kaltenborn, T. Magier - Joint resistance of bolted copper - copper busbar joints depending on joint force at temperatures beyond 105 ° C 56th IEEE Holm Conference on Electrical Contacts, 2010

Evaluation of long-term behavior

Quality of a joint is evaluated by the performance factor k_u



$$k_u = \frac{R_{Joint}}{R_{Material}} = \frac{P_{Joint}}{P_{Material}}$$

Technically good bus-bar connections have a performance factor of $k_u \leq 1.5$

Temperature of the joint: $\vartheta_J \sim I^2 \cdot R_J$

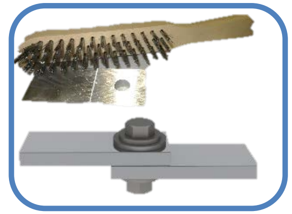
⇩

If resistance of the joint increases in time:
➔ Failure of the joint

Procedure for long-term tests

Pretreatment / Assembly

- Suitable treatment depending on contact material
  - Abrasive treatment of bare materials and Ni coatings
  - Cleaning with ethyl alcohol
- Assembly of bus bars with 25 kN clamping force



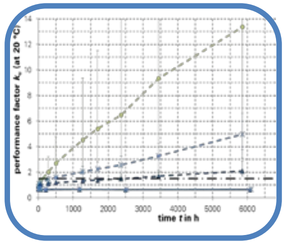
Aging of the joints

- Aging of the joints at 115 °C; 140 °C

  (application of current or constant temp. in oven)
- Measurement of the resistance of the joint

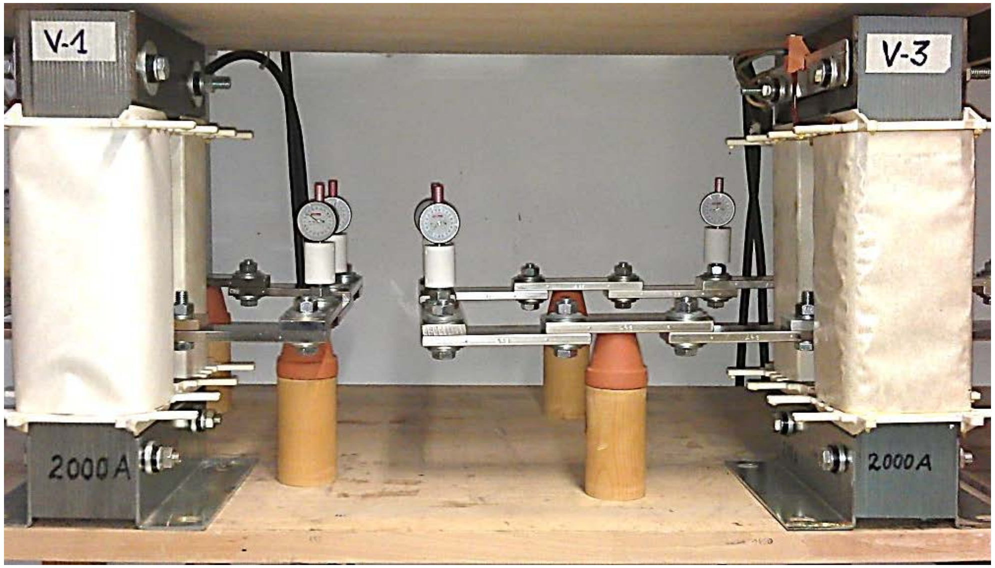
Evaluation / classification of the joint

- The performance factor is evaluated
- The long-term stability is assessed



Long-term test arrangements at high temperatures

Arrangement with continuous current (CC)



Constant temperature in oven (OV)

- **Both arrangements are equivalent !**
- Difference is that with continuous current a runaway effect occurs at the end, since the temperature of the joint increases due to resistance AND power dissipation increase.

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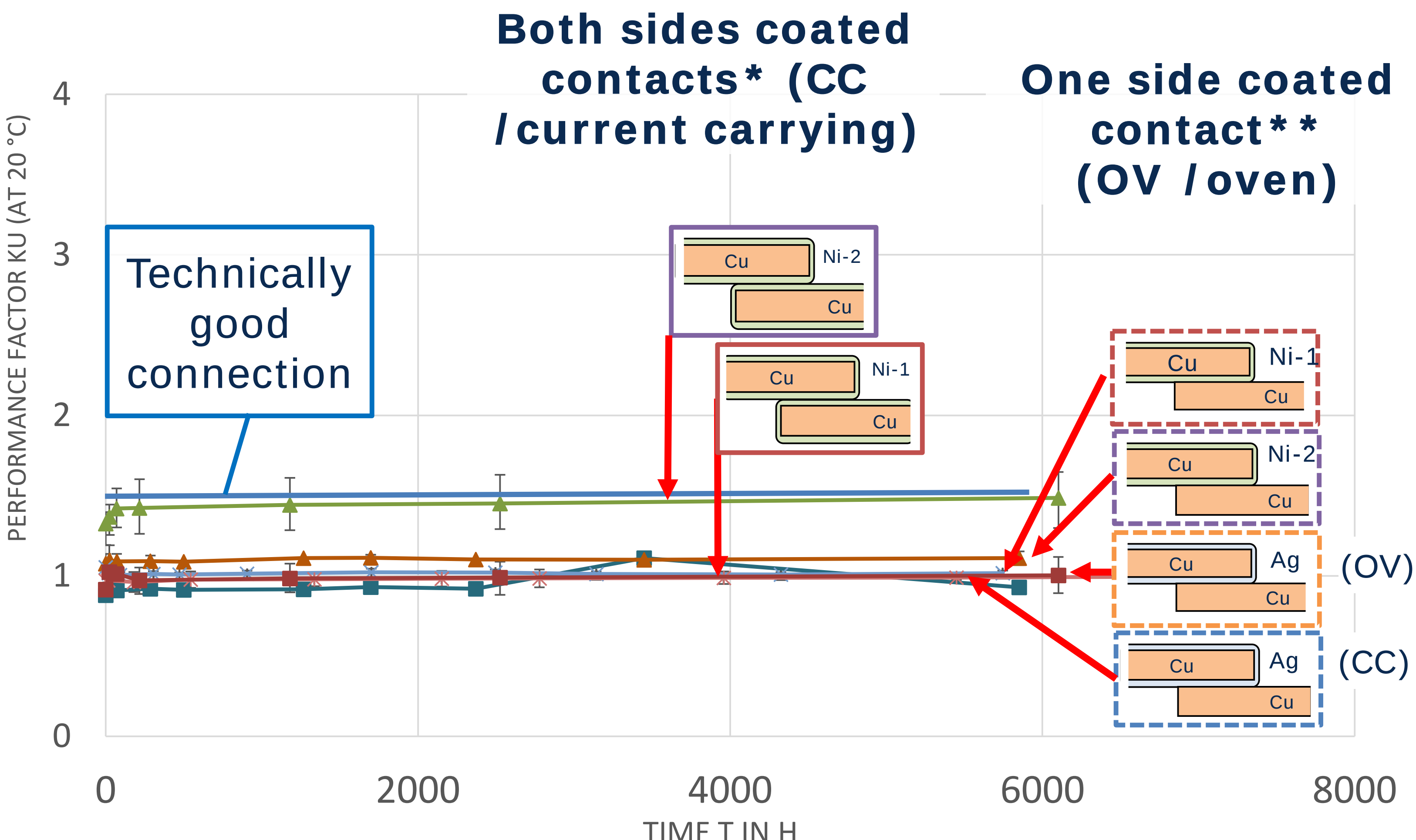
Specification of coating materials for long-term tests at UNI Dresden

Bulk material of bus bars	Nickel* coating		Silver coating		
	types		intermediate layer		
	Ni-1	Ni-2	without	Cu	Ni-2
Cu-ETP R300**			×		
Cu-ETP R250	×	×			
Al99,5	×	×		×	×
AlMgSi0,5	×	×		×	×

* Difference between nickel coatings is the galvanic coating process

Silver-coated and Nickel-coated copper (115 °C)

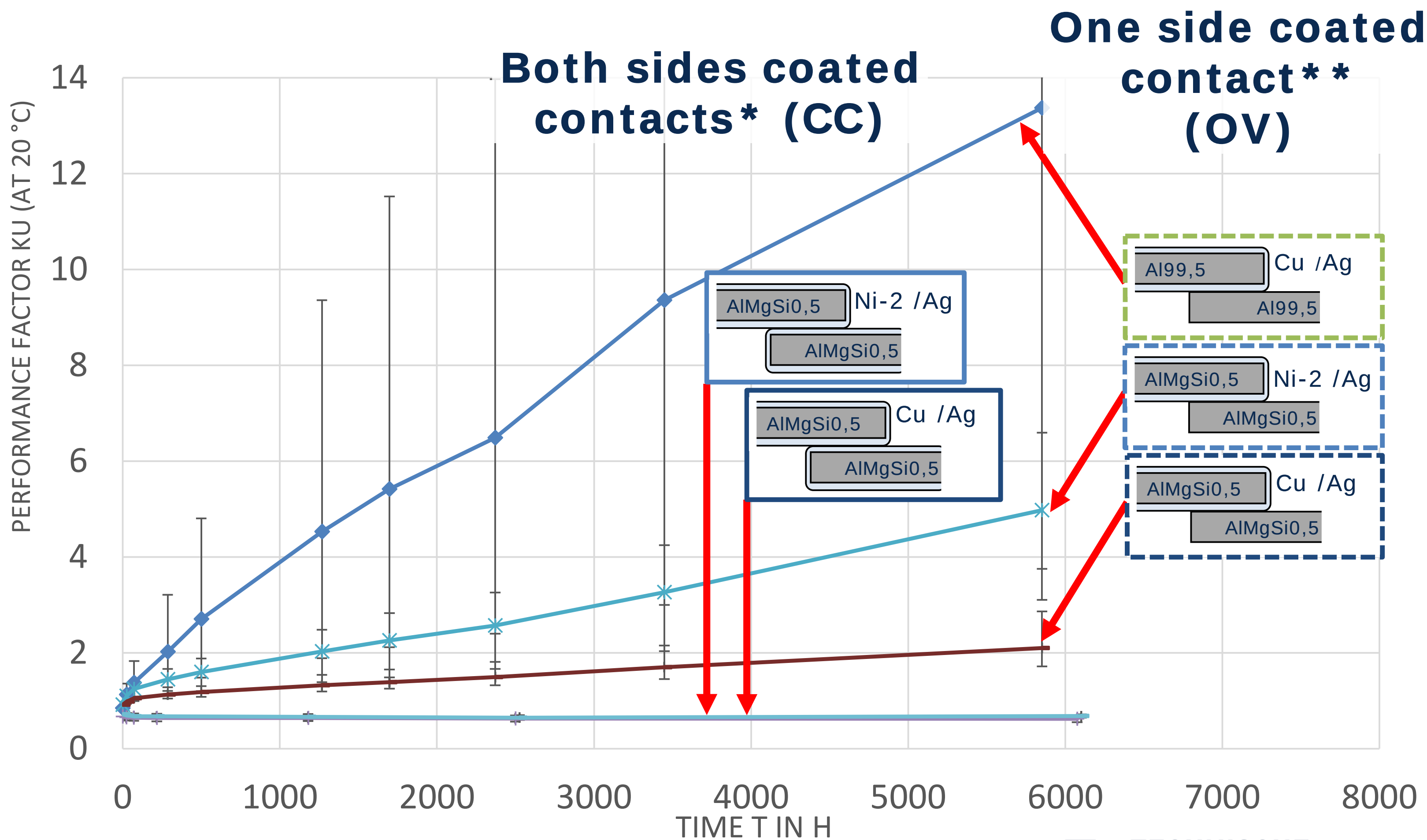


Silver-coated and Nickel-coated copper (115 °C)

Connections with silver or nickel-coated copper are long-term stable

- no tendency of degradation over the observed duration
- For Ag-coating, tests prove that connections are stable even at 140°C over more than 30000 h
- Good performance with both sides or one side coating
- **For this combination, the higher temperature of silver or nickel coated copper is appropriate !**
- Abrasive treating and cleaning of the bare copper surface is recommended, however not crucial.

Silver-coated aluminum (115 °C)

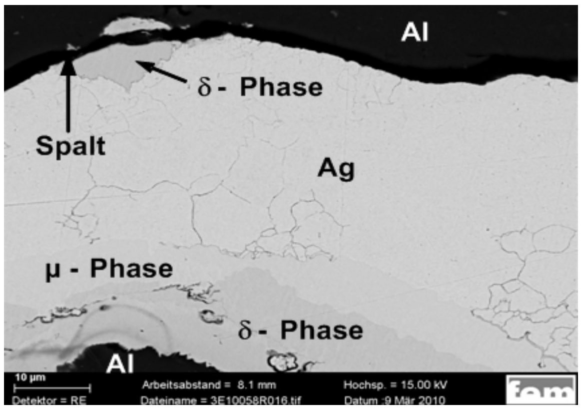


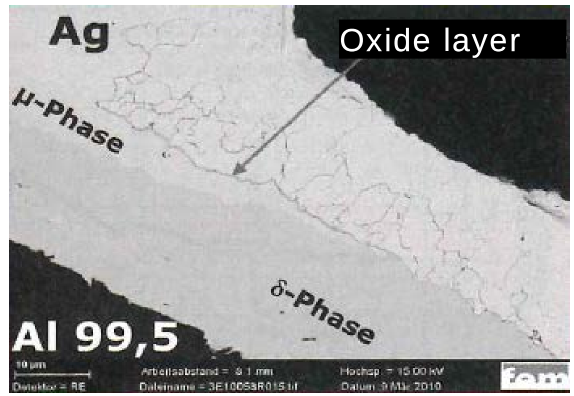
Silver-coated aluminum (115 °C)

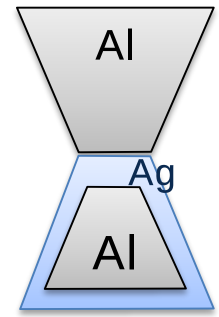
Connections with silver-coated aluminum on one side only and bare aluminum are not long-term stable !

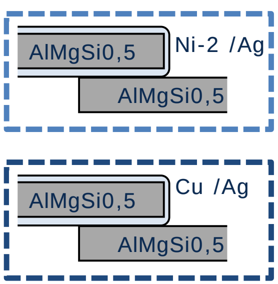
- IEC and ANSI IEEE allow this combination
- However, in a short time this combination would fail at 115°C
- **For this combination, even the lower temperature of bare aluminum might be too high.**
- Brushing and greasing of the bare Aluminum surface needs to be applied, however is not crucial.

Explanation for failure of one side Ag-coated Al









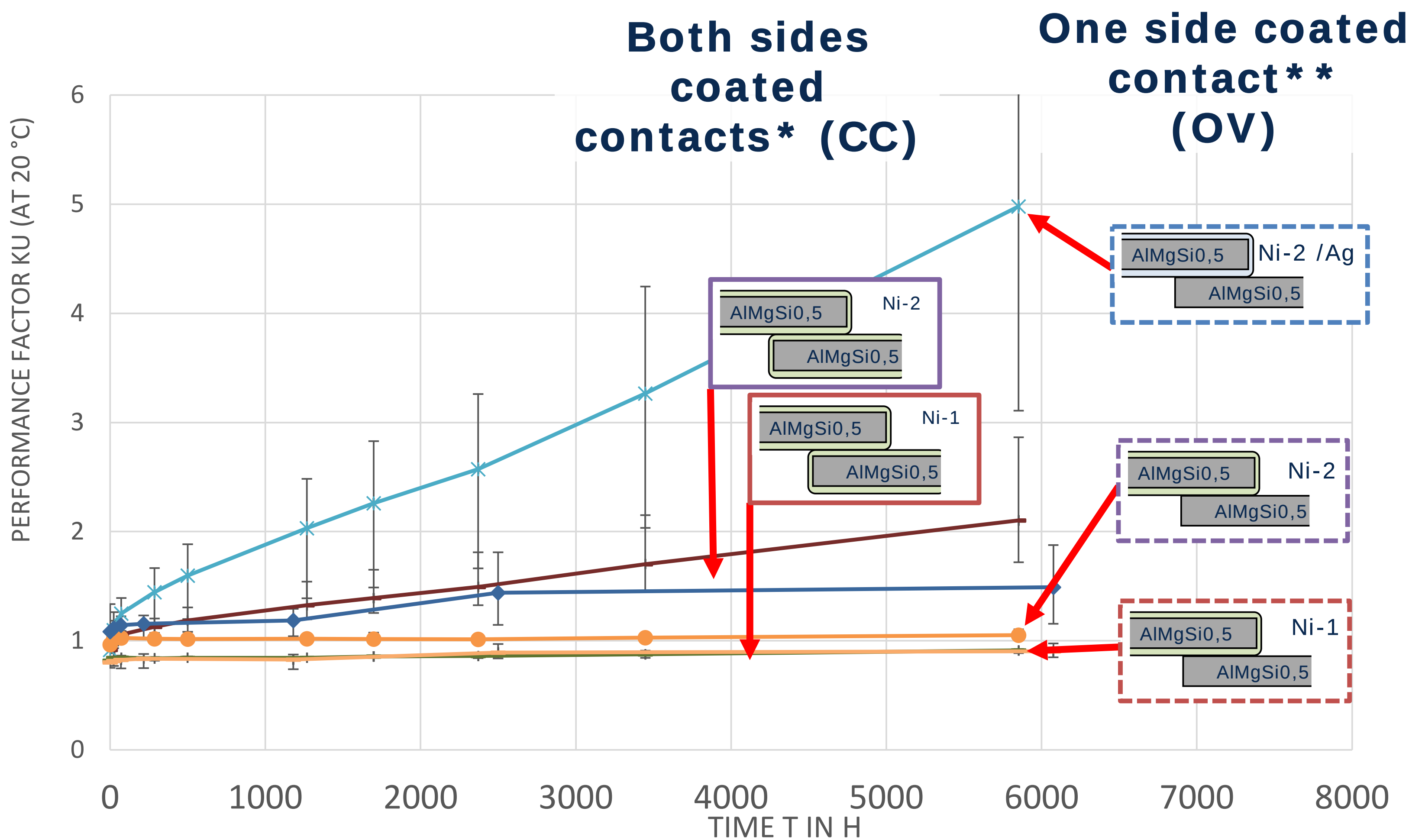
Formation of intermetallic compounds at the small contact-spots between silver-coated and bare aluminum (Al-Ag)

Therefore a Cu undercoat needs to be applied always

Formation of an oxide layer between Al-substrate and silver coating

Further investigations are needed to explain resistance increase

Nickel-coated aluminum (115 °C)



Nickel-coated aluminum (115 °C)

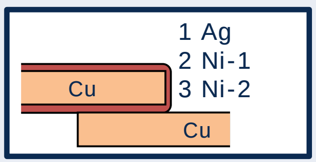
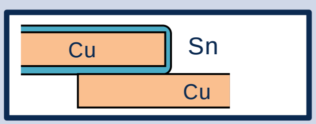
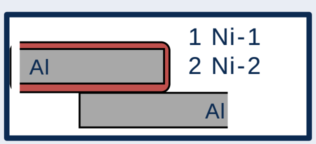
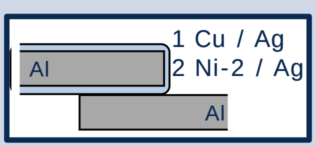
Advantage of connections with nickel-coating compared to silver-coating of aluminum:

- Good performance irrespective of both sides or one side nickel coating
- However, performance depends on type of nickel coating !
- Also, Nickel-coating has a high film resistance

Summary of experience of TU Dresden

Connections with only one side coated material

(IMC means Inter-Metallic Compound)

Bimetal system	Long-term behavior at 115 °C		Long-term behavior at 140 °C	
	Eval.	Comments	Eval.	Comments
	✓	No IMC in these bimetal systems	✓	No IMC in these bimetal systems
	✓	Thin IMC-layer → not critical	✓	Slightly increased R_J (IMC) → not critical so far
	✓	R_J has remained constantly low	✓	Slightly increased R_J
	✗	Unstable (presumable O_2 – Diffusion)	✗	Unstable (presumable O_2 – Diffusion)

Proposal for IEC and IEEE standards

- **The application of one side silver-coated aluminum should not be allowed.**
- **The application of one side nickel-coated aluminum can be allowed up to the higher limit temperature of the coating.**
- **The application of one side silver- or nickel-coated copper should be allowed up to the higher limit temperature of the coating.**

Thank you

»Wissen schafft Brücken.«