# Welding through the Ages

Prof. Dr.-Ing. (IWE) Martin J. Greitmann
Martin.Greitmann@hs-esslingen.de







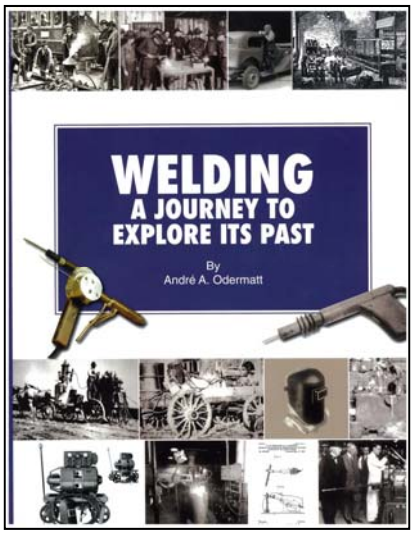
## Personal Bibliography resistance welding

**DVS - German Welding Society**
Chairman of DVS working group V 3.3
„Resistance welding in electronics and precision mechanics"

**International Institute of Welding (IIW)**
Expert of Commission III
„Resistance welding, solid state welding
and allied joining processes"

**Professional / consulting engineer:**
Greitmann Consulting, www.greitmann.com
www.ip-esslingen.com

## History of welding




*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*


Bookstore on the Hobart Institute
www.welding.org





## Contents

### Welding through the Ages

**History of welding**

Dimesions (macro & micro engineering)

Quality assurance

Numerical simulation

Education & training


**Electrum: 75% Au, 25% Ag**

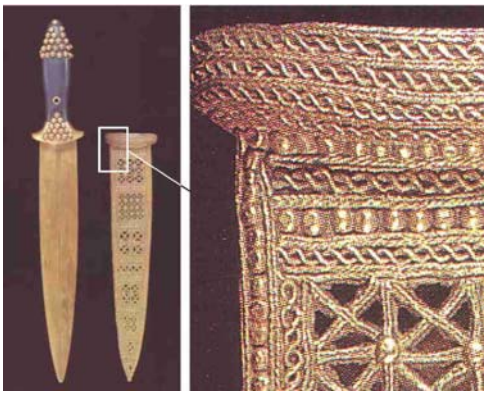
## 2600 B.C. – Electrum cup and golden headdress kings grave at Ur (Mesopotamia / today Iraq)

*(welding and cutting, journal No. 9 (2005))*









**Soldering:**
**pellets and twisted wires**

## 2600 B.C. – golden knife dagger
### kings grave at Ur (Mesopotamia / today Iraq)

*(welding and cutting, journal No. 9 (2005))*

## Early soldering with charcoal and blow pipe

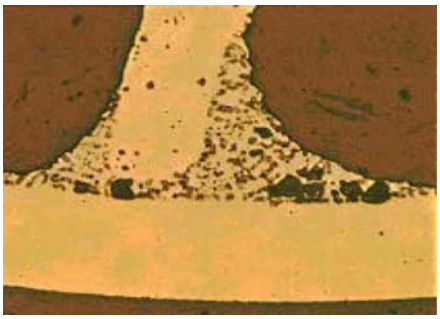
**1330 B.C. – golden death mask of Tut-Ench-Amun (Egypt)**

*(welding and cutting, journal No. 9 (2005))*









**Solder joint at the knob**
(soldering metal: Au-Ag-Cu alloy)

**Reaction Soldering: 1330 B.C. – golden knife dagger (Egypt)**

*(welding and cutting, journal No. 9 (2005))*

## Iron Age – Forge welding, pieces of wrought iron

310 AD - The iron pillar of Dehli (India)

| | |
|---|---|
| **Height:** | about 7.375 m |
| **Diameter:** | 41.6 cm (bottom)<br>34 cm (top). |
| **Weight:** | estimated > 6 t |
| **Material:** | wrought iron<br>C (0.03–0.28)<br>Si (0.004–0.056)<br>P (0.114–0.48) |

*(www.ias.ac.in/currsci/jun252005/1948.pdf ; www.wikipedia.org )*







**Bronze Age**

Small gold circular boxes were made by pressure welding lap joints together.

**Iron Age**

During the Iron Age the Egyptians and people in the eastern Mediterranean area learned to weld pieces of iron together. Many tools were found which were made approximately 1000 B.C..

**Middle Ages** (**forge welding**)

During the Middle Ages, the art of blacksmithing was developed and many items of iron were produced which were welded by hammering.

## Forging (Solid State Welding)

Figure 8.1.2: Damascus sword made of wootz steel

Figure 8.1.3: Patterned steel created by forgimg

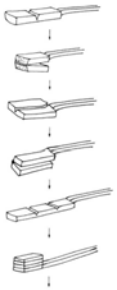
Figure 8.1.10: Water-powered hammer-forge at Bentsberg, Germany

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*





## Forging (Solid State Welding)

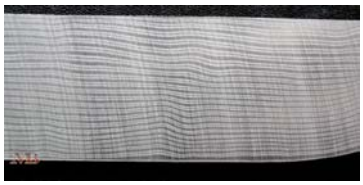


**Application:**
Multilayer material (“Damascus steel”) manufactured by folding and welding by hammering

| Cycle | 1 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| Layers | 4 | 8 | 32 | 128 | 512 | 2048 |

(Yoshindo Yoshihara, Hiroko Tateno Kapp und Leon Kapp von Kodansha: The Craft of the Japanese Sword, Intl ( 1.April 1987))

## Forging (Solid State Welding)
### Application: Knife blades



| Steel | C | Si | Mn | Cr | Ni | Mo | V |
|---|---|---|---|---|---|---|---|
| 90 MnCrV 8 (1.2842) | 0.90 | | 2.0 | 0.4 | | | 0.1 |
| 45 NiCrMo 16 (1.2767) | 0.45 | 0.25 | 0.35 | 1.35 | 4.05 | 0.25 | |
| X46Cr13 (1.4034) | 0.42 - 0.50 | max. 1.0 | max .1.0 | 12.5 - 14.5 | | | |
| X55CrMo14 (1.4110) | 0.48 - 0.60 | max. 1.0 | max .1.0 | 13.0 - 15.0 | | 0.5 - 0.8 | |

*( Schmiedewerkstätte Markus Balbach; www.schmiede-balbach.de )*



Hochschule Esslingen
University of Applied Sciences
History of welding

## Forging (Solid State Welding)
### Application: Knife blades

*( www.friedrich-hartkopf.de )*

*( Schmiedewerkstätte Markus Balbach; www.schmiede-balbach.de )*

## 1900 Oxyacetylene welding

(Charles Picard (1872-1957) inventor of the first oxyacetylene torch)

An oxyfuel gas welding process that uses acetylene as the fuel gas. The process is used without the application of pressure *(AWS)*

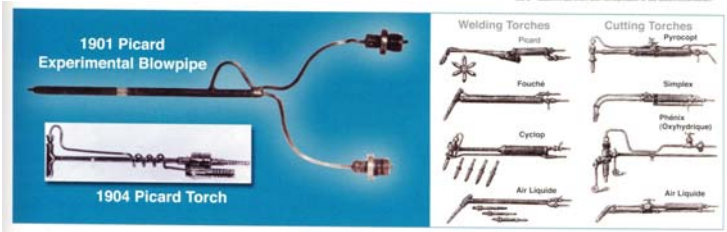
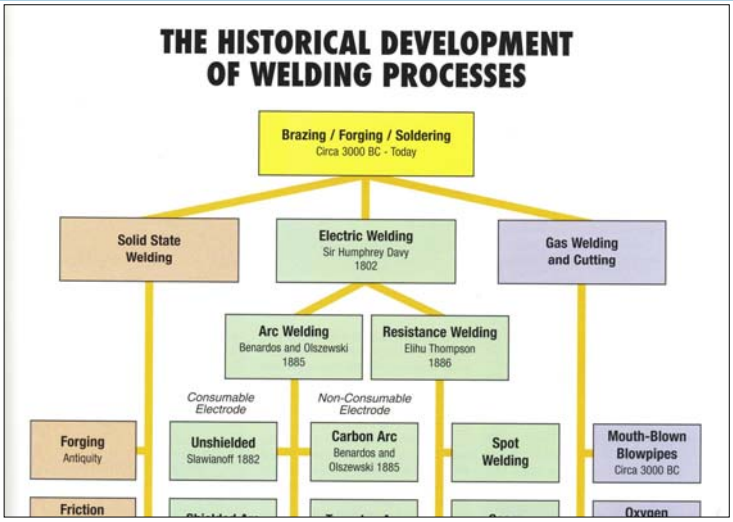




*Figure 2.4.6: Henry Louis Le Chatelier (1850-1936) brought to public attention that the temperature of the oxyacetylene flame is 3100-3200° C (5612-5792° F) – appreciably higher than the oxyhydrogen flame at 2500° C (4532° F).Charles Picard (1872-1957), Paris France, is the inventor of the first oxyacetylene torch and Edmond Fouché announced it in Paris on November 3, 1901.*

*(DVS, WELDING - A JOURNEY TO EXPLORE ITS PAST)*








*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*

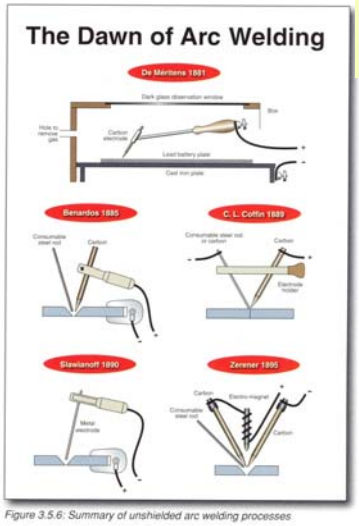
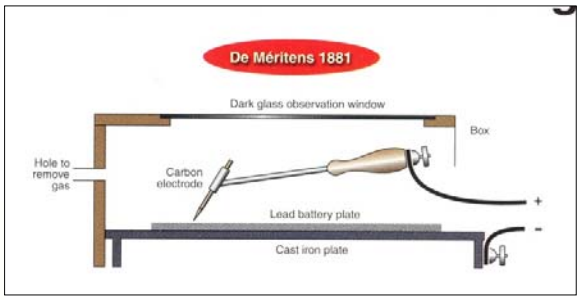



Figure 3.5.6: Summary of unshielded arc welding processes

## 1881 Carbon Arc Welding
(Auguste De **Mèritens** (1834-1898))




The process was carried out in a box with a fixed electrode.

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*





## 1885 1887 Carbon Arc Welding
(N. **Benardos** & S. **Olszewski** used an insulated handel)

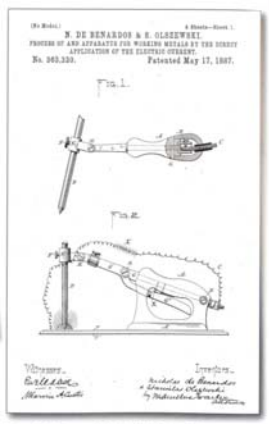


Figure 3.3.2: Electrode holder in U.S. Patent 363,320

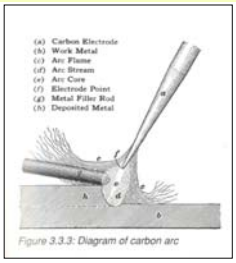


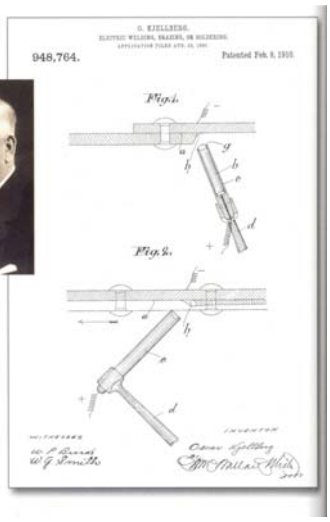
Figure 3.3.3: Diagram of carbon arc

Carbon Arc Welding uses an arc between a carbon electrode and the weld pool.
The process is used with/without shielding or application of pressure *(AWS)*

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*

**1907** **Shielded metal arc welding**

Oscar **Kjellberg** (1870-1931)
Protecting the arc and the molten metal by a covered electrode




Shielded metal arc welding uses an arc between a covered electrode and the weld pool. The process is used with shielding from the deposition of the electrode covering without the application of pressure, and with filler metal from the electrode *(AWS)*

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*





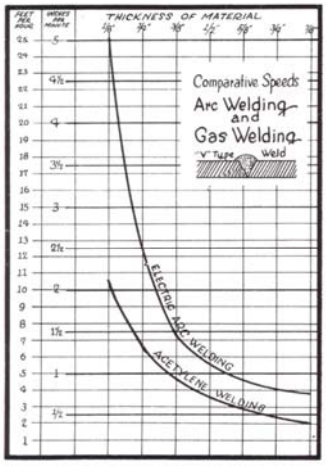



Figure 3.3.10: Comparative speed with which good welds can be made, 1930's

**1930's** Low cost of arc welding compared with riveting and gas welding

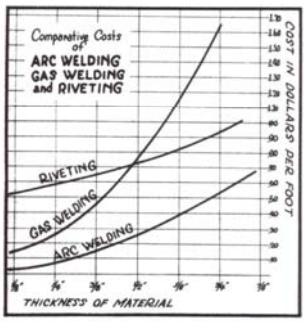
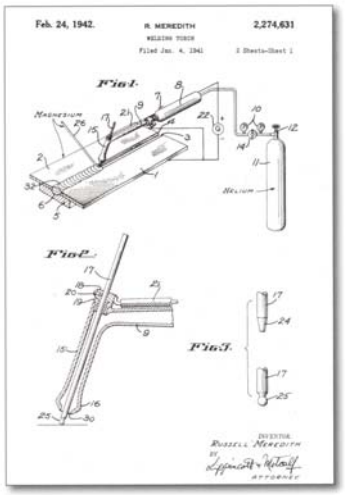


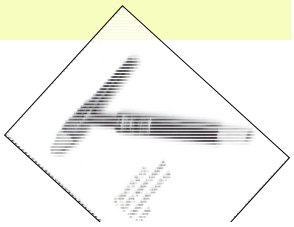

Figure 3.3.11: Low cost of arc welding compared with riveting and gas welding, 1930's

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*




**1940** **Gas Tungsten Arc Welding**
(Russel **Meredith** developed an electric arc method for welding magnesium)

*Heliarc® TIG torch by Linde*



Gas Tungsten arc welding uses an arc between a tungsten electrode (nonconsumable) and the weld pool.
The process is used with shielding gas and without the application of pressure. *(AWS)*

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*





**1940, 1945** **Gas metal arc welding**
developed at Battelle Memorial Institute, Columbus / Ohio

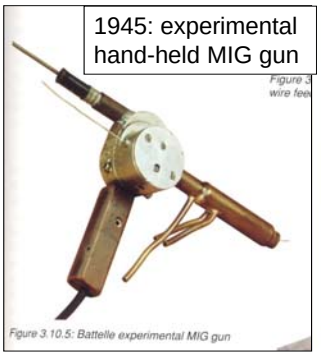



Figure 3.10.5: Battelle experimental MIG gun

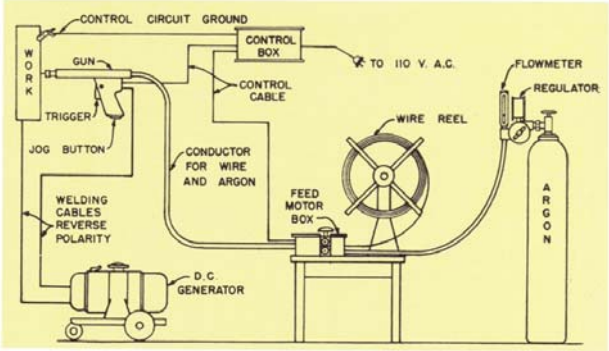



Figure 3.10.10: Schematic diagram of equipment for inert gas metal arc welding of aluminum

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*

## History of welding

**1943** **Gas metal arc welding**
inventors: C.B. **Voldrich**, P.J. **Rieppel** and Howard B. **Cary**

**1948** Jesse S. **Sohn** & A.N. **Kugler**:
„Shielded-Inert-Gas-Metal-Arc“ process was introduced by the Air Reduction Co. at the AWS show in Philadelphia

Gas metal arc welding uses an arc between a continuous filler metal electrode (consumable) and the weld pool.

The process is used with shielding from an externally supplied gas and without the application of pressure. *(AWS)*


**1948:**
Aircomatic® MIG gun

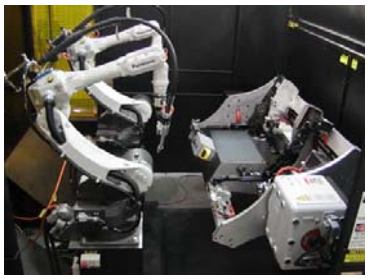
*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*



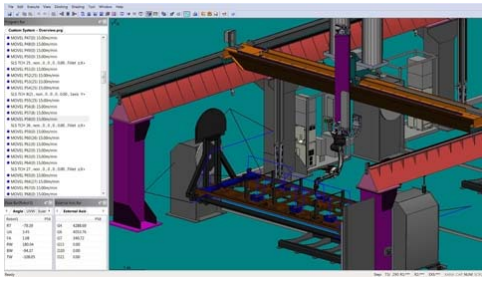




## History of welding

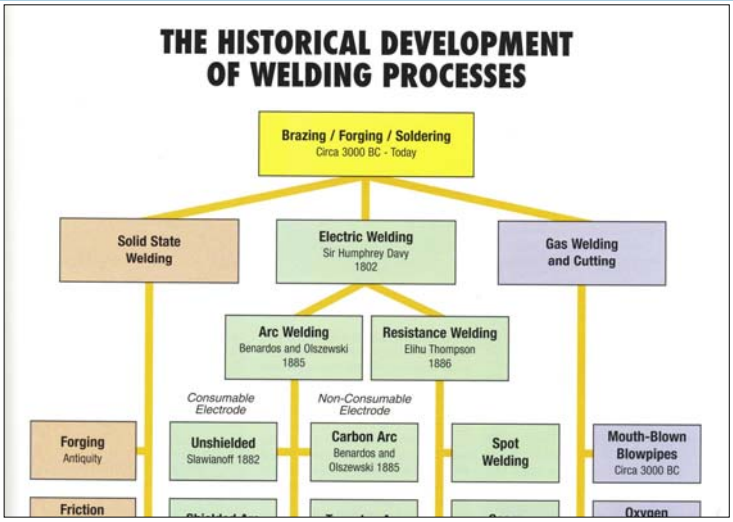


**Robot welding systems since 1980**



*(Miller Electric Mfg. Co., www.MillerWelds.com)*

## History of welding




*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*





## History of welding / 19th century

**1857** **James Prescott JOULE** (UK)
described the possibilities to weld metals by resistance heating

James P. Joule (1818-1889)

**1866** **Werner von SIEMENS** (D)
invents the dynamo (requirement to commercial produce electricity / high current)

**1879** **Thomas Alva EDISON** (USA)
invention of a technical usable filament bulb

## History of welding / 19th century

**1877** **Elihu THOMSON** (USA, 1853-1937),
lecturing at Franklin-Institute, Philadelphia
experimental work to the fundamentals of resistance welding

**1881** **Special machines**
It is known that special machines have been used for manufacturing resistance welded cables
welding current: 60 … 100 A
secondary circuit voltage: 20 V





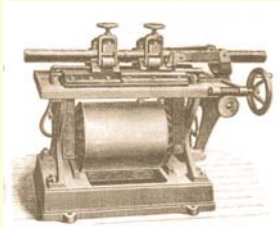


## History of welding / 19th century

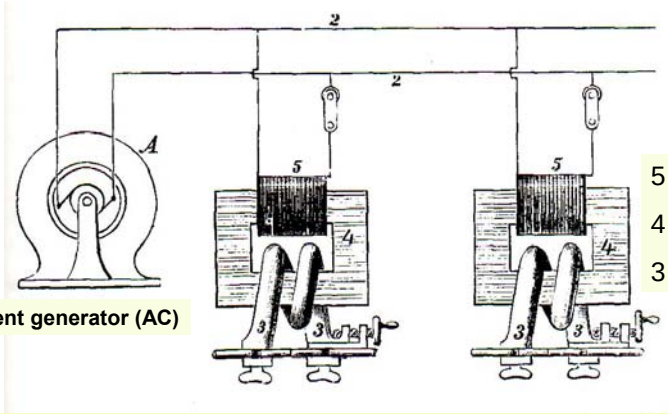
**1886** **Elihu THOMSON:**
applied for 2 process patents
No. 347140 and 347141
„Apparatus for Electric Welding“
Lynn, Massachusetts (USA),
(10th August 1886 German Patent DE No. 39765)

**Resistance welding**
(ISO 857-1, Proc. No. 2):

„Welding with pressure in which the heat necessary for welding is produced by resistance to an electrical current flow through the welding zone.“ *(today)*



## History of welding / 19th century




2 electric main

5 primary circuit

4 core (iron)

3 secondary circuit

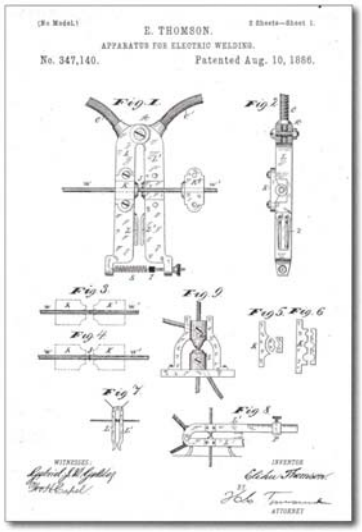
A current generator (AC)

**1886** **Elihu THOMSON:**
process patents No. 347140 and 347141
„Apparatus for Electric Welding“





## History of welding / 19th century




**1886** **Elihu THOMSON:**
process patents No. 347,140
„Apparatus for Electric Welding“

or art of electric welding
to join metal wires

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*

## History of welding / 19th century

*Figure 7.4: Elihu Thomson with first electric welding transformer with a single-turn secondary built in early 1886*

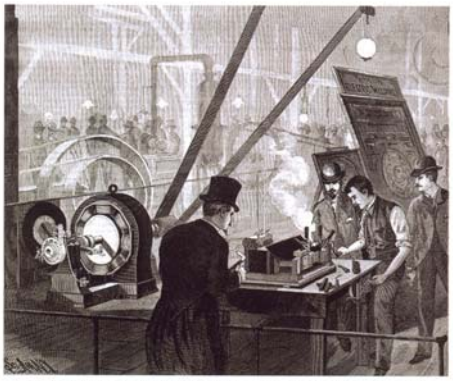


*Figure 7.9: Elihu Thomson demonstrating electric resistance welding at American Institute Fair, New York, 1887*

**1887** **Elihu THOMSON**
at American Institute Fair, New York

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*







## History of welding / 19th century

**1887 / 88** **Nicolai N. NENARDOS**
(1842-1905, russian scientist)
Resistance spot welding of iron sheet using carbon electrodes.
(Patent DE No. 46776 and No. 46779)

**about 1897** **KLEINSCHMIDT**
Use of copper electrodes
(The substitution of the carbon electrodes was basic for further rapid development and application of resistance welding)

## History of welding / 19th century

**1887, 1888** **George Westinghouse** (1846-1914)
**Nicola Tesla** (1856-1943)

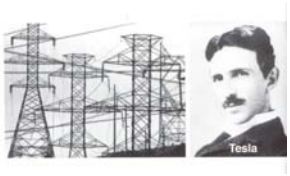




Figure 3.2.2: First Tesla AC motor

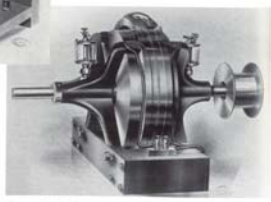


Figure 3.2.3: First Tesla AC generator

Patents of power generation and distribution

(WELDING - A JOURNEY TO EXPLORE ITS PAST)



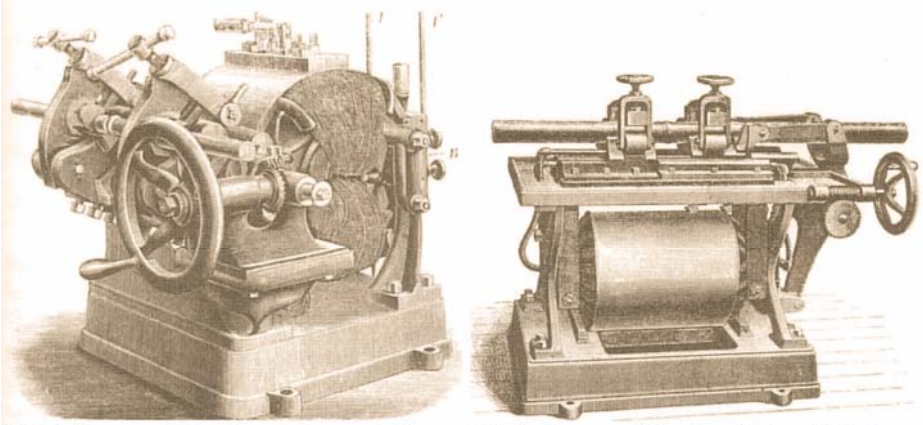




## History of welding

**1903** **First machine for resistance butt welding**
After merger between
Allgemeine Elektricitäts-Gesellschaft (AEG) and
Union-Elektricitäts-Gesellschaft (UEG, Berlin)
they were owner of the THOMSON-patents.

**1906** **First resistance spot welding machines**
are used in the sheet metal forming industry
(up to 1910 about 367 machines for spot and seam welding)



**1903** **Resistance Butt welding machines from E. Thomson**





**1903** **Resistance Butt welding machine**

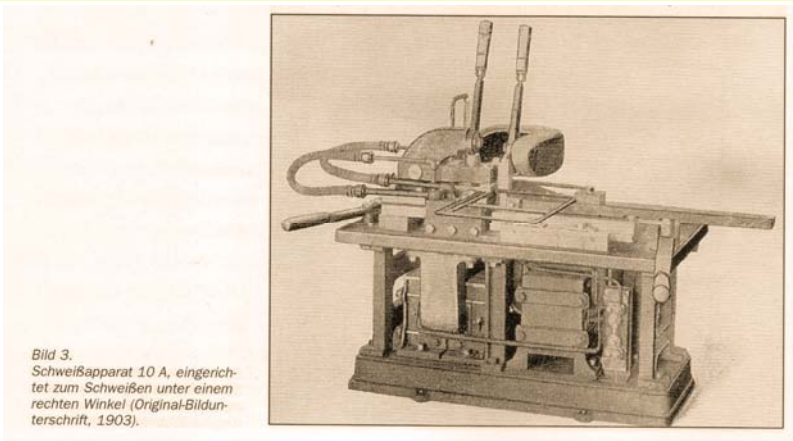


Bild 3.
Schweißapparat 10 A, eingerichtet zum Schweißen unter einem rechten Winkel (Original-Bildunterschrift, 1903).

*(AEG)*

## 1904 **Resistance butt welding machine** / Type KA IV (Application: chain manufacturing)

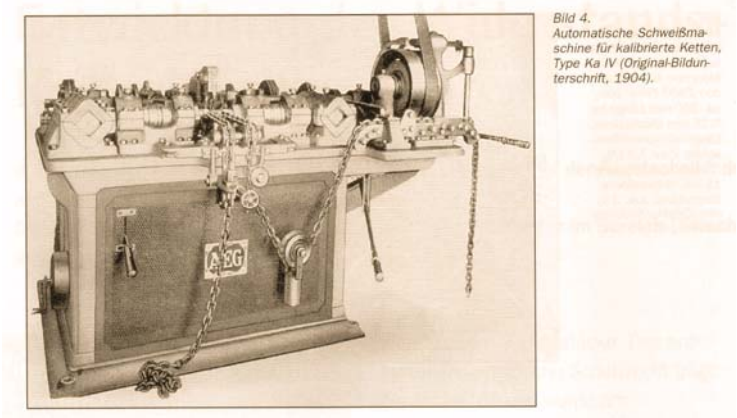



Bild 4.
Automatische Schweißmaschine für kalibrierte Ketten, Type Ka IV (Original-Bildunterschrift, 1904).

*(AEG)*



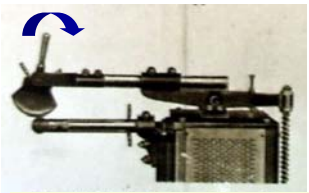


## since 1906 **Resistance spot welding**

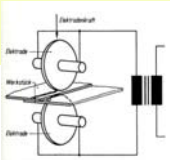



*(PECO)*

## 1911… Seam welding



Machine with electrodes for short longitudinal welds

Applications (1929): thin walled tubes and cones

*(PECO)*





## 1911 Seam welding machine / Type 7,5 LN (max. power 15 kW, max. $t_{SUM}$ = 2.5 mm )

*(welding and cutting, journal No. 9 (2005))*

**One girl welded in 10 h**

**2400 buckets (t = 0.28 mm)**

**weld seam length: 300 mm**

## 1973 Seam welding

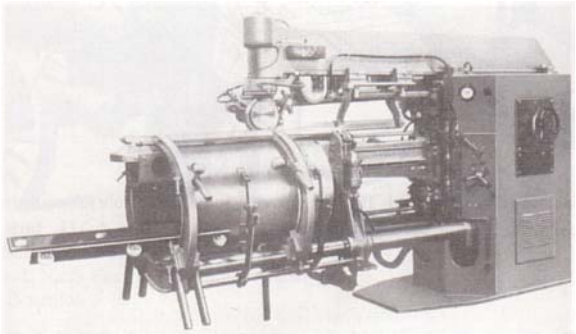


**Bild 7.** Nahtschweißmaschine zum Schweißen von Blechzargen, zum Beispiel für Fässer mit Durchmessern von 350 bis 640 mm, der Messer Griesheim GmbH, PECO Elektroschweißtechnik, München 1973.

Applications:
sheet frames,
barrels (d = 350 … 640 mm)



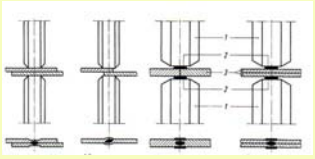




## 1980 Seam welding

Einphasig-zweipulsige Gleichrichter-Nahtschweißmaschine Typ GVN (Ausführung Längsnaht)

*(PECO, Messer Griesheim GmbH)*



*(Schlatter Industries AG, Application: Radiator)*

**1916** Cam disk controled **flash welding machine**
(process fundamentals in 1912)

Welded cross section:
1930: 10 000 $mm^2$,
1941: 70 000$mm^2$;
1961: 100 000 $mm^2$
(power: 4,5 MVA
welding current: 300 kA
frequency: 9 Hz )





**1929** Flash welding
(Application: lokomotive components)

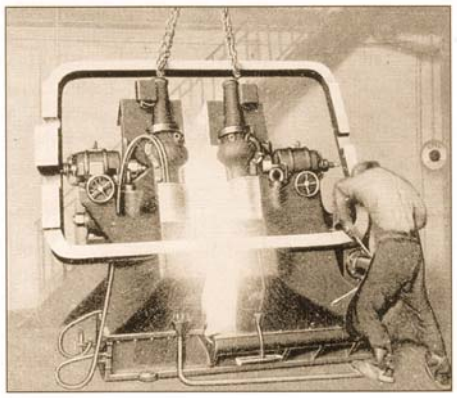
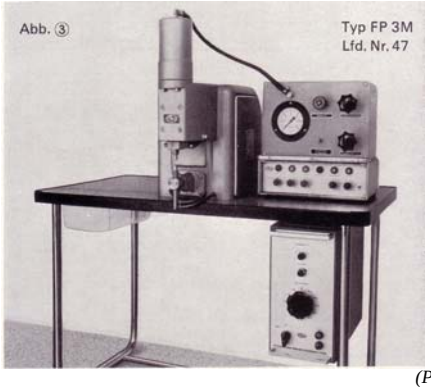


Bild 5.
Stumpfschweißung eines Lokomotiv-Feuerbuchsbodenringes (Original-Bildunterschrift, 1929).

*(welding and cutting, journal No. 9 (2005))*

**1962…** Resistance welding (spot or projection welding) (applications: small parts in fine mechanics and electronics)

**Bild 8.** Feinpunktschweißen an Kleinteilen mit einer Maschine der Firma PECO, München-Pasing 1962.




*(PECO)*





**today** Resistance welding in fine mechanics and electronics

*(PECO, Messer Griesheim GmbH, MIYACHI Europe GmbH)*

## 1970 … today Development - Welding pressure heads


pneumatic | pneumatic + spring | servo-motor | piezo-electric actuator

*(PECO, Messer Griesheim GmbH, MIYACHI Europe GmbH)*





## 1970 … today Development – Welding power supply

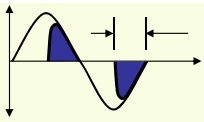
Alternating current (AC)

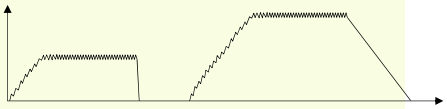
Direct current (DC)

Capacitor discharge

Transistor controlled

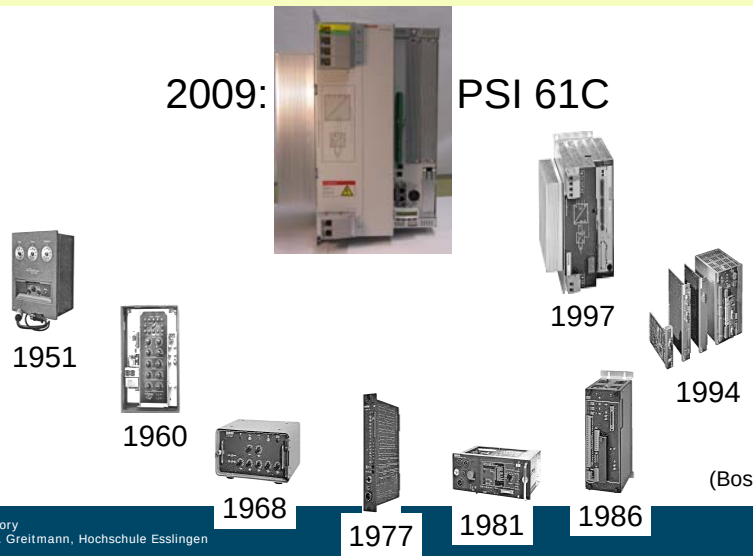
Inverter technology > 20 000 Hz





Available control modes: current – voltage – power - energy

## 1951 … 2009 Welding Controls from Bosch Rexroth




(Bosch Rexroth)



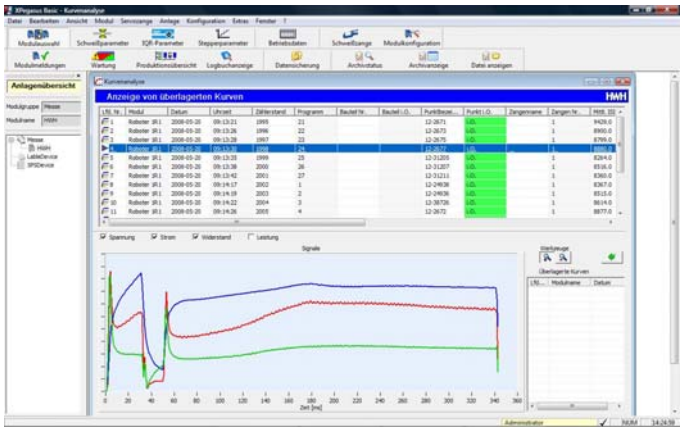


## 1951 … 2009 Functionality of Inverter Control PSI61C

- **Process regulation / monitoring integrated**: Process interfaces for current, voltage and force, Adaptive UI-regulator and force supervision **on board**
- **USB Interface** for local programming and
- **Ethernet IP / ProfiNet** for central programming and operation **on board**
- **Diagnostic/operation unit** for status check, setting of IP adress a.o.

(Bosch Rexroth)

## today — Process: control - documentation - inspection



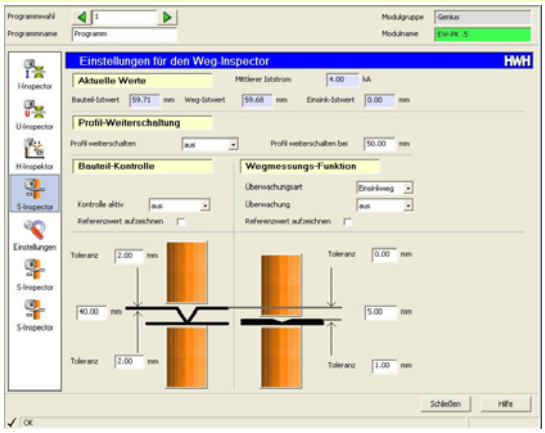

HARMS+WENDE HWH



Hochschule Esslingen
University of Applied Sciences

History of welding

## today — Process: control - documentation - inspection




Parameter:
Component geometry
Sliding movement

HARMS+WENDE HWH

**since 1930** **Resistance spot welding in car body manufacturing**

Widerstandsschweißen 1930

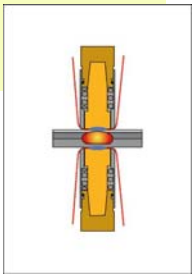
Widerstandsschweißen Heute

*(Fronius)*





**today** **Car body manufacturing System: DELTA SPOT (Fronius)**



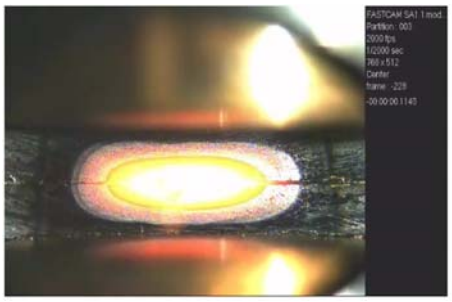

**Application:**
spot welding aluminium

70 m of process metal band afford 5 000 – 10 000 repeatable spot welds with one elektrode (no weld spatter).

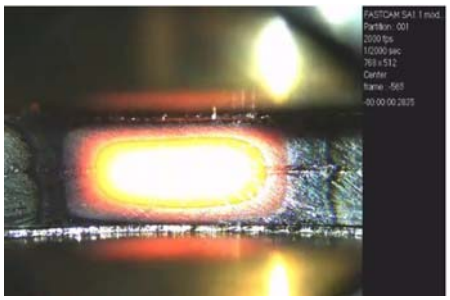
*(Fronius)*

**today** **Car body manufacturing**
**System: DELTA SPOT (Fronius)**

conventional



DeltaSpot



*(Fronius)*

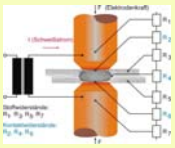
Source: HYUNDAI



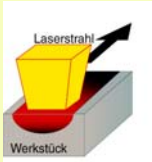


# Anniversaries in 2011

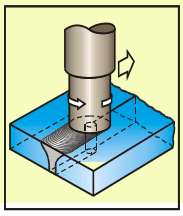
**125 years** **Resistance welding**
(since the THOMSON patents)



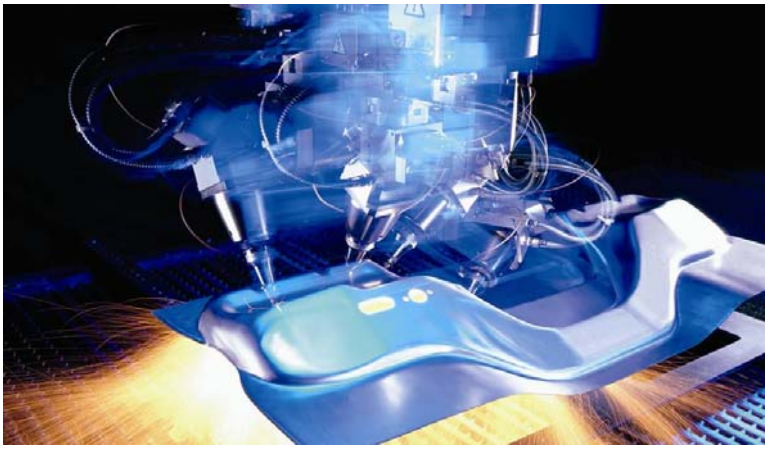
**51 years** **Laser beam technology**




**20 years** **Friction stir weldig**



## since 1960 Laser Beam Technology

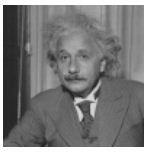


*(TRUMPF Laser)*





## 1917 - 1962 THEORY → MASER → LASER



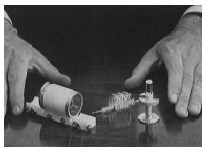
Theory of stimulated Emission

(Albert Einstein)

1. Maser

*( **M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation )*

(Charles H. Townes)



1.(Ruby)-Laser

*(**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation )*

(Theodore Maiman)

1. Gas laser

(A. Javan)

He - Ne

$\lambda$= 1,15cm

Science-Fiction

1. red He-Ne Laser (A. White)

$\lambda$ = 633nm

1. Neodymiumlaser

(L.F. Johnson)

1917 | 1954 | 1960 | 1960 | 1962

*(TRUMPF Laser)*

12. Dezember

16. Mai

## 1964 - 1990 Development of LASER technology


1. $CO_2$ - Laser
(C. Kumar, N. Patel)

1. Argonlaser
(W. Bridges)

1. Nd:YAG Laser
(J.E. Geusic)

Begin of Nd:YAG Laser technology

Fa. C. Haas GmbH

1. TRUMPF combined Stamping-Laser-machine

TRUMATIC 180 L
power: 500 - 750W

1. TRUMPF $CO_2$ - Laser

TLF1000
power: 1kW

C. Haas developed first Laser-light cable for materials processing

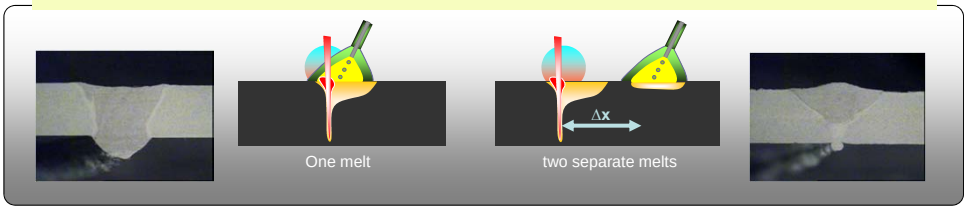
1964 1971 1979 1985

*(TRUMPF Laser)*





## 2008 LASER-ARC-HYBRID WELDING



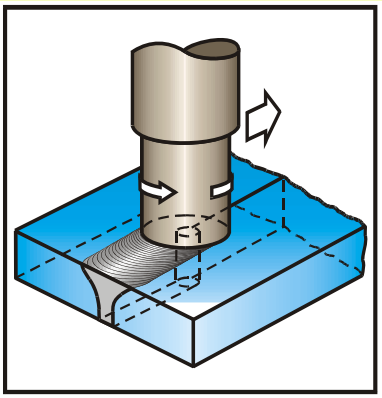


### Nd:YAG-Laser-MIG

| | |
|---|---|
| $V_{weld}$: | 40 mm/s |
| Shielding Gas: | Argon, 12l/min |
| Filler wire: | SG-AlSi5<br>d = 1,6 mm |
| Base metal: | EN AW-AlMg3Mn,<br>t = 3,5 mm |

*(Höfer)*

## 1991 Friction Stir welding



Material: AlMgSi1

**Patent – process (TWI, 1992)**

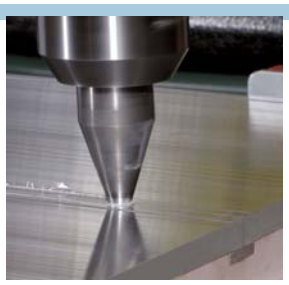
**Friction stir welding (MPA Stuttgart, 1995)**

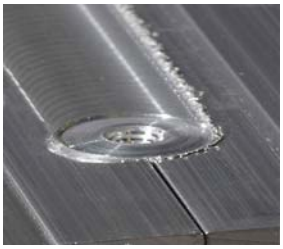





*(MPA Stuttgart)*

**welding machine (ESAB FSW Legio-3ST)**

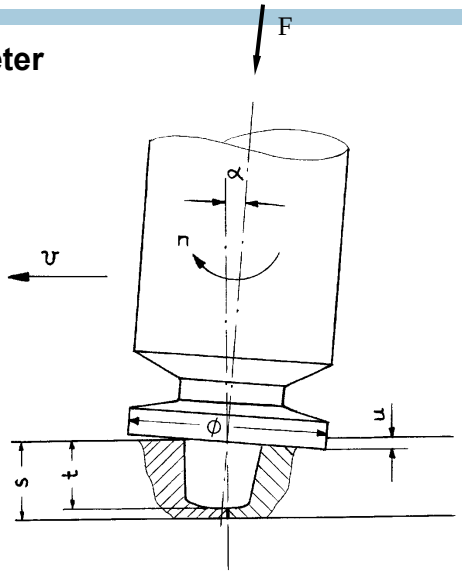




**friction stir seam weld**

## Tool- and processing parameter

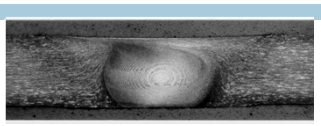
- tool material
- shoulder diameter (∅)
- pin geometry
- penetration (t)
- overlap (u)
- tilt angle (α)
- number of revolutions (n)
- welding speed (v)
- downward force (F)
- clamp forces

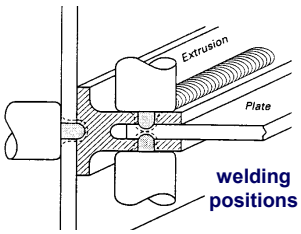




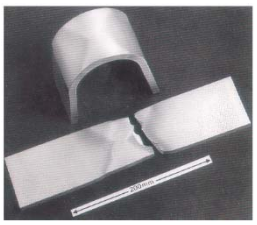



## Advantages

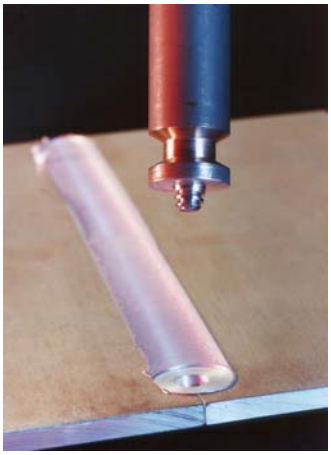





- simple and robust process
- simple joint preparation
- no fused-on spatters, fume or dust,
- no impact on environment
- no inert protective gas
- low power requirement
- low distortion of the welded parts
- very good mechanical behaviour of the welds
- material mix of different aluminium alloys

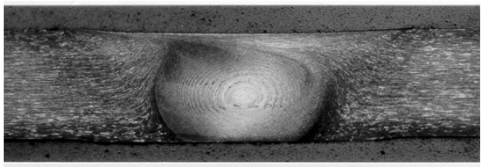


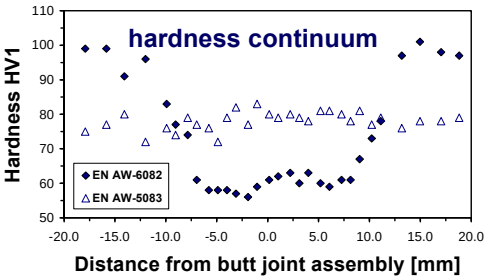
**Application:** Aluminium



welding seam and tool

macro-examination specimen






◆ strength reduction due to solution of precipitates





**Application:** Audi R8 - Friction stir welded closing plate of the centre tunnel after forming

material: EN AW-6181 T4,
sheet thickness t: 1.7 mm / 2.4 mm

(Audi AG, Riftec GmbH)

## History of welding

**Volvo XC 90 with 19” hybrid wheel**

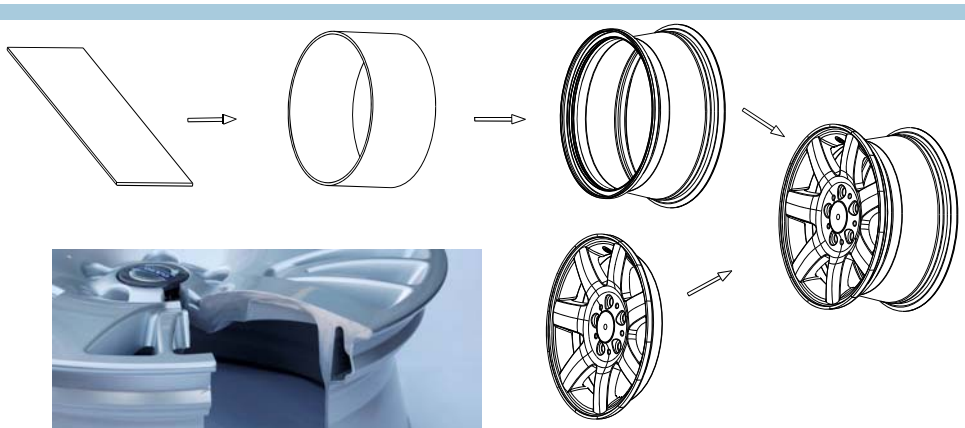
FUNDO WHEELS







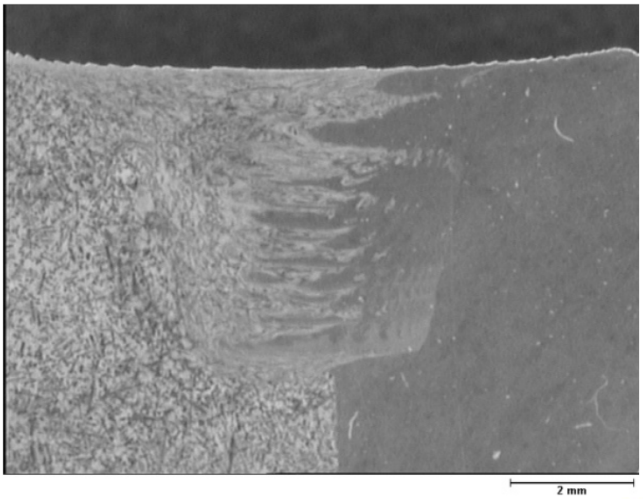
## History of welding



**Principle for**
**Hybrid Wheel manufacturing**

FUNDO WHEELS

## History of welding

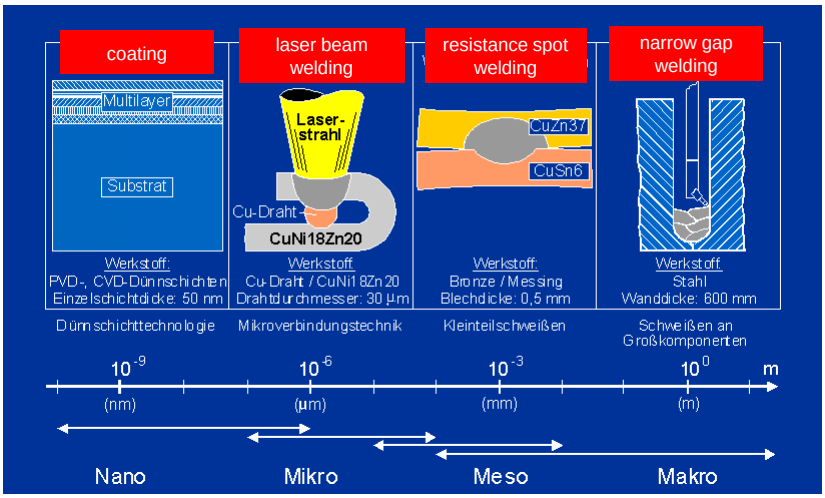



**Friction Stir Weld**



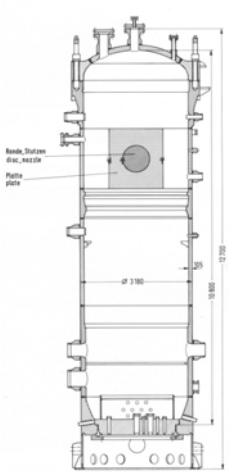


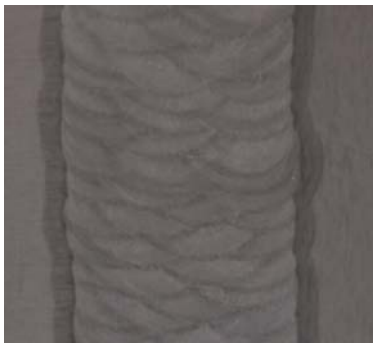
## Dimensions of welding




*(MPA Stuttgart)*

## Multilayer weldment (Pressure vessel components)





**t = 270 mm**
**about 420 weld layers**

*(MPA Stuttgart)*





## Narrow gap welding
**Application: big components**

**200 mm**

**t = 200 mm**
**about 120 weld layers**

*(MPA Stuttgart)*

## Electron beam welding
**Application: big components**


*(MPA Stuttgart)*



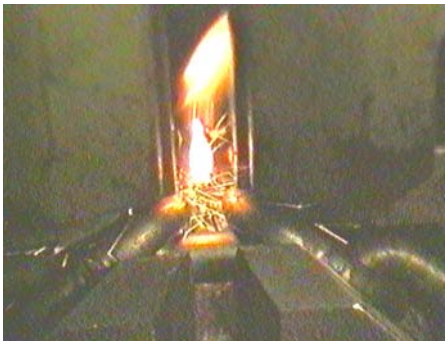


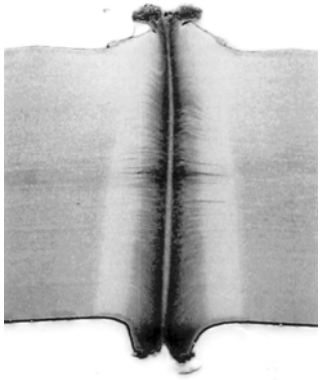
## Flash welding (ISO 857-1 Proc. No. 24)
**Application: welded rails**
**welded cross section area: approximately 8000 mm²**

*(Schlatter Industries AG)*

## Resistance butt welding (ISO 857-1 Proc. No. 25)

**Application: chain**
**welded cross section area: 150 mm²**





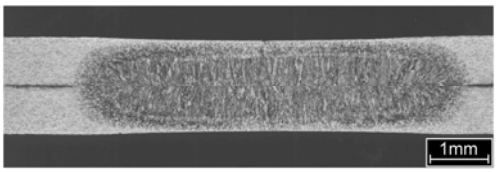
*(RUD)*





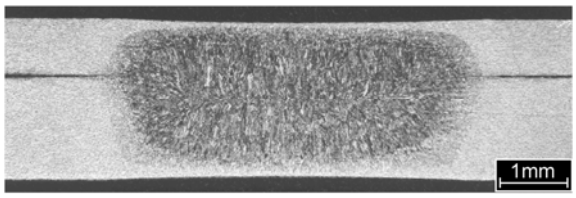
## Spot welding (ISO 857-1 Proc. No. 21)

**Application: car body manufacturing, sheet frames**
**welded cross section area: 20 mm²**




in Germany (1997):

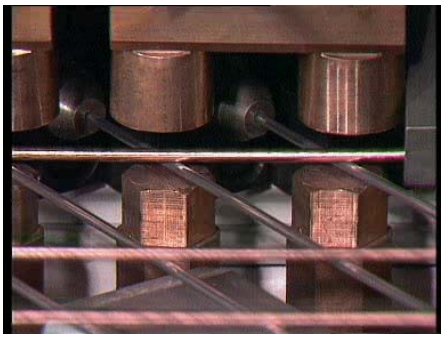
75 000 000 spot welds/day

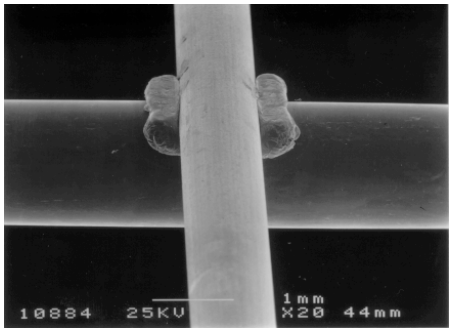



*(Krause,BAM, MPA Stuttgart)*

## Projection welding (ISO 857-1 Proc. No. 23)

**Application: wire cross sections**
**welded cross section area: 80 … 0.5 mm²**






NiTi-wires

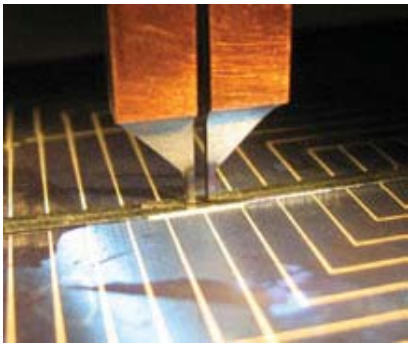
*(Schlatter Industries AG, MPA Stuttgart)*

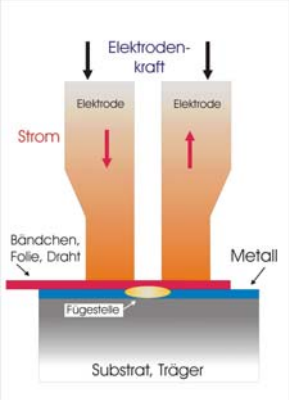




## Parallel gap welding

**Application: solar components, sensor systems**
**welded cross section area: 0.5 mm²**

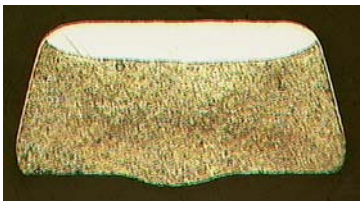


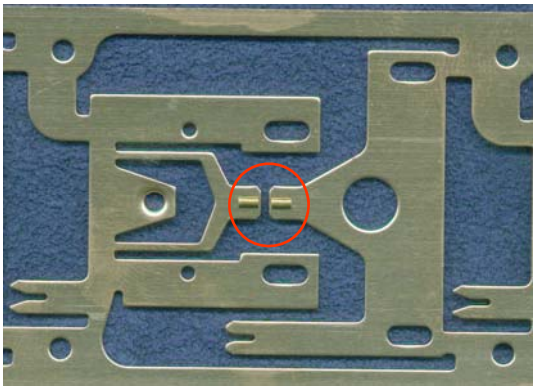



*(PECO, MIYACHI Europe GmbH)*

## Projection welding (ISO 857-1 Proc. No. 23)

**Application: electrical contacts**
**welded cross section area: 25 mm² … 0.1 mm**





**Geometry: 0.13 x 0.30mm**
**Materials: 0.5µm Au diffusion**
**PdRu10**
**CuNi30Fe**

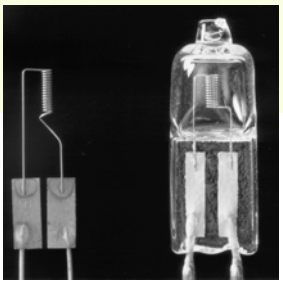
*(Prym INOVAN GmbH)*



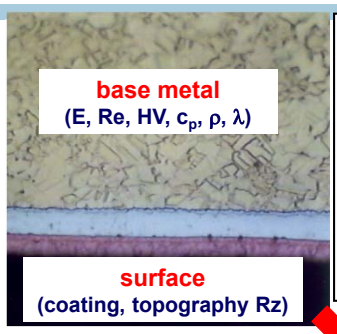


## Projection welding (ISO 857-1 Proc. No. 23)

**Application: thin (enamelled) wires**
**welded cross section area: 0.08 mm²**

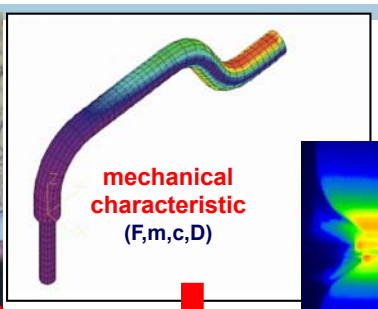


## Quality assurance



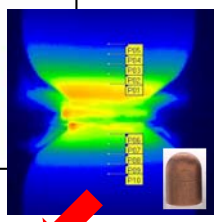
**base metal**
(E, Re, HV, $c_p$, ρ, λ)

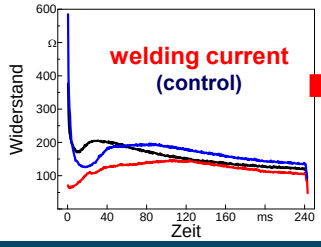
**surface**
(coating, topography Rz)



**mechanical characteristic**
(F,m,c,D)

**electrode** (material, geometry, Rz, wear, water cooling)






**welding current**
(control)

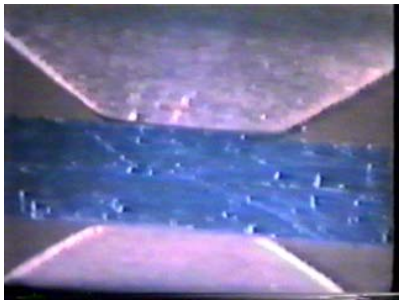
**Quality criterions for spot welds:**
(mictrostructure, nugget diameter, strength, toughness, surface...)







## Quality assurance



Die
elektrische Widerstandschweißung
im Lichte der Metallographie.

Von der Technischen Hochschule München zur Erlangung der Würde eines Doktors der Technischen Wissenschaften (Dr.-Ing.) genehmigte Abhandlung.

Vorgelegt von

Dipl.-Ing. Dr. ing. Felix Goldmann

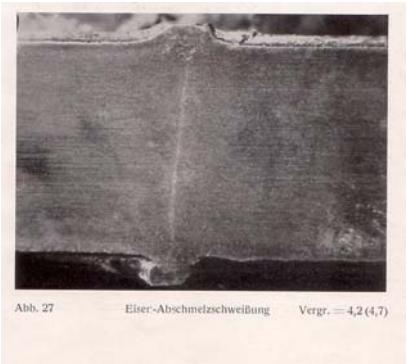
DRUCK VON FRIEDR. VIEWEG & SOHN AKT.-GES. BRAUNSCHWEIG

**Process analysis (video)**

*(INSTYTUT SPAWALNICTWA, GLIWICE)*

**Metallography**

## 1929: Dr.-Ing. Dr. iur. Felix Goldmann
**(Doctoral thesis, Technische Hochschule München)**



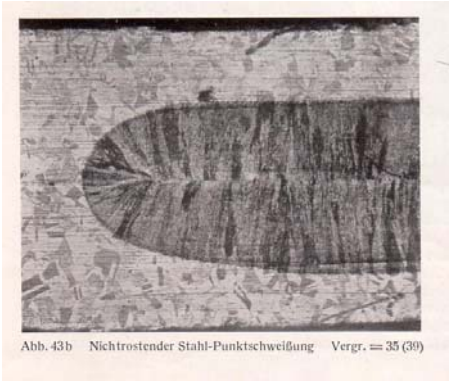


**flash weld (iron)** **mash seam weld (iron)**



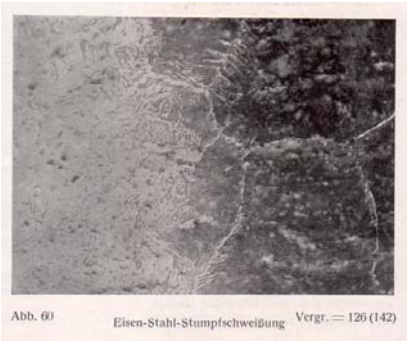


## 1929: Dr.-Ing. Dr. iur. Felix Goldmann
**(Doctoral thesis, Technische Hochschule München)**




**spot weld (stainless steel)**

## 1929: Dr.-Ing. Dr. iur. Felix Goldmann
(doctoral thesis, Technische Hochschule München)





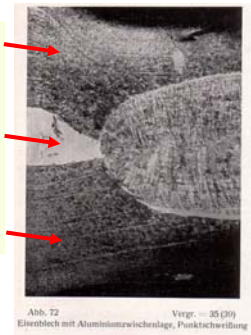
**iron / steel (butt weld)** **iron / steel (spot weld)**





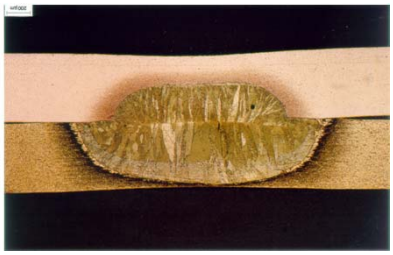
## 1929: Dr.-Ing. Dr. iur. Felix Goldmann
(Doctoral thesis, Technische Hochschule München)


iron sheet
Al-interlayer
iron sheet




**Zinc coated iron sheets** **iron sheets with Al-interlayer**

## 1929: Dr.-Ing. Dr. iur. Felix Goldmann
**(doctoral thesis, Technische Hochschule München)**

*(MPA Stuttgart,1998)*

**Copper / Brass** **Bronze / Brass**

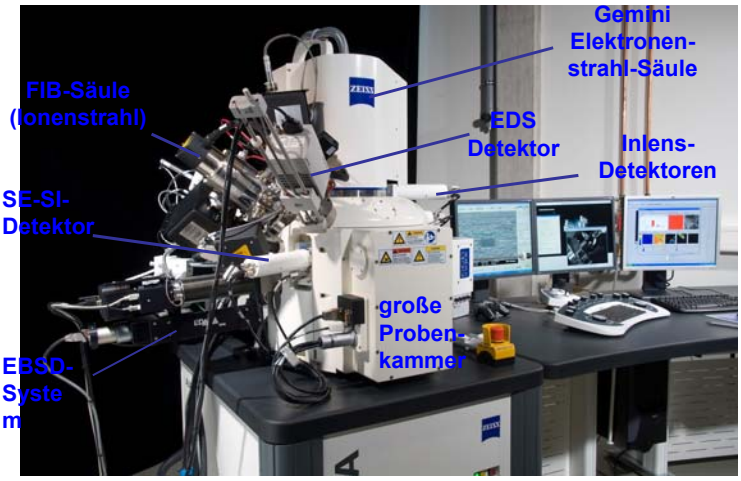
**Resistance spot welds**





Zeiss *Auriga* Crossbeam

**Detektorkonfiguration**




**Elektronenstrahl**

Schottky Feldemitter

1,0 nm @ 15 kV

1,9 nm @ 1 kV

**Ionenstrahl**

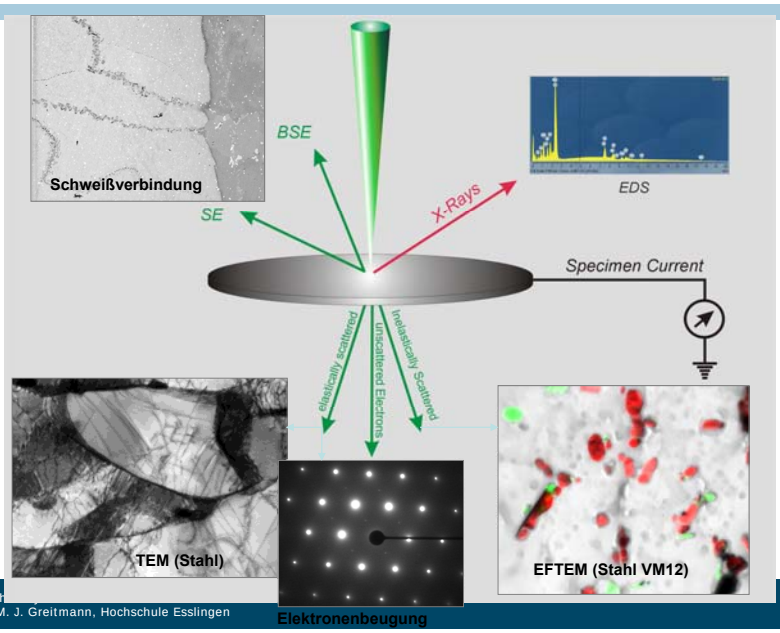
Gallium-Ionenquelle

< 7 nm @ 30 kV

*(MPA Stuttgart)*

Hochschule Esslingen
University of Applied Sciences

## Quality assurance
## Scanning electron microscopy (SEM)




(MPA Stuttgart)



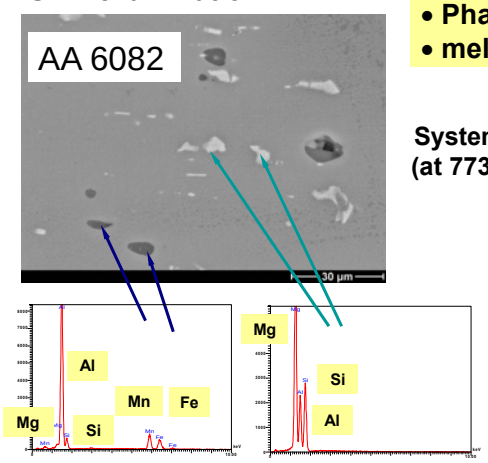
Hochschule Esslingen
University of Applied Sciences

## Quality assurance
## material science – thermal simulation

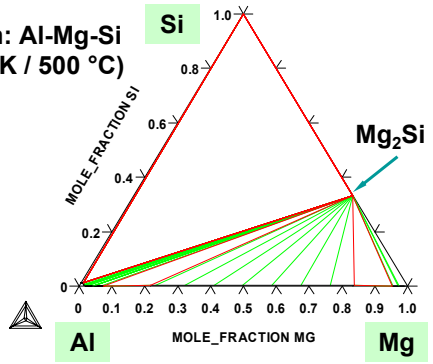
**Thermal simulation (Thermo-Calc®)**

**Results:**
- **Phase diagramme**
- **melting of intermetallic phases**

**SEM examination**

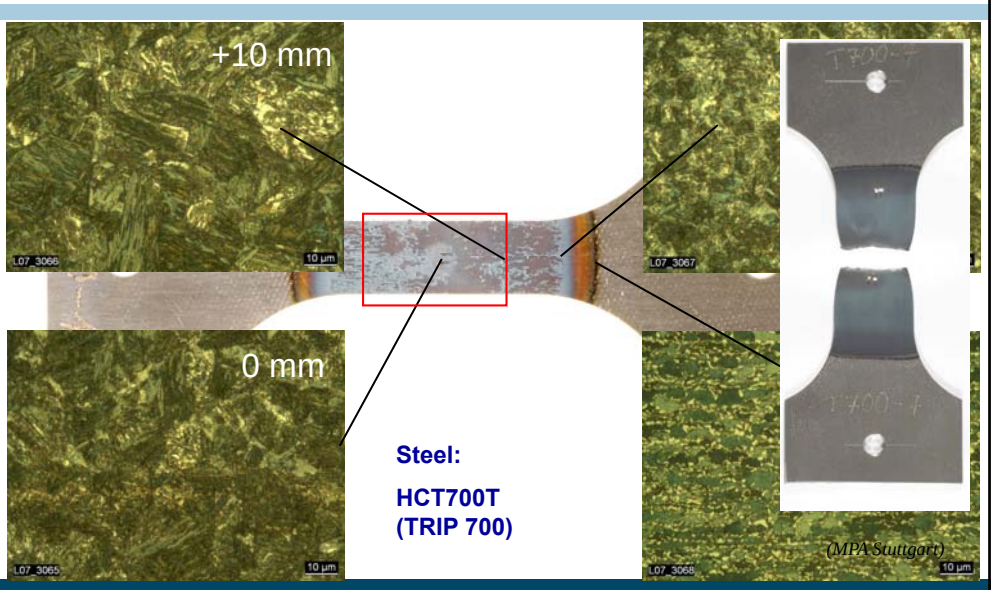



**System: Al-Mg-Si (at 773 K / 500 °C)**



Hochschule Esslingen
University of Applied Sciences

## Experimental thermal simulation weldability

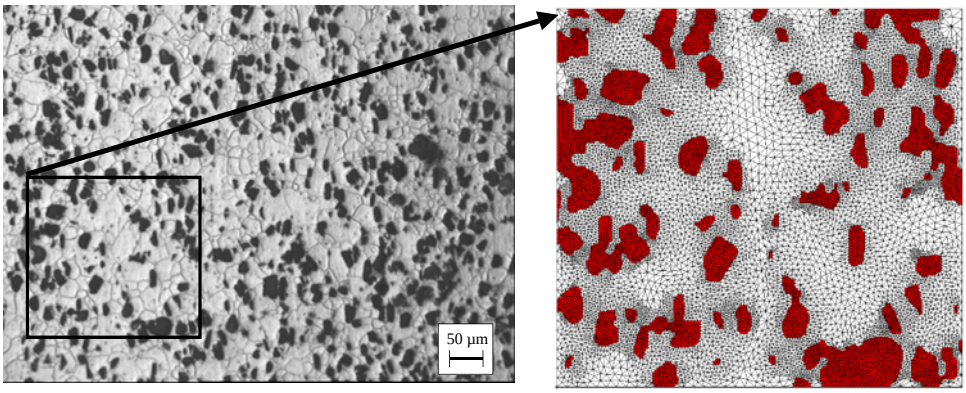





Hochschule Esslingen
University of Applied Sciences

## Quality assurance microstructure mechanics

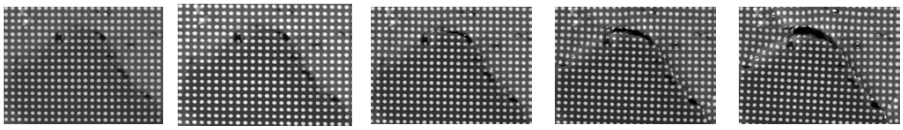
**(Al / 15vol.%$Al_2O_3$)**



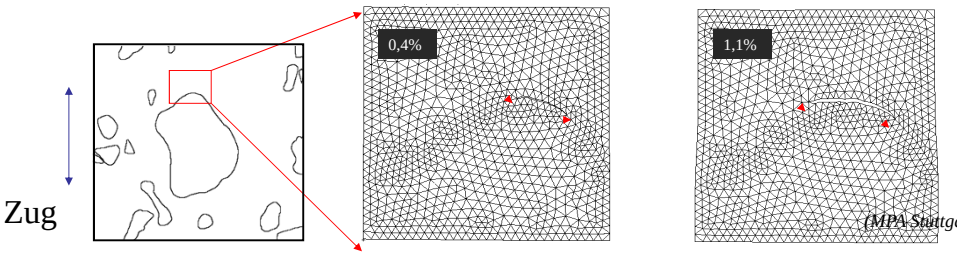

Microstructure and FE-mesh

*(MPA Stuttgart)*

## Crack growth in AA6061/$Al_2O_3$ (tensile load)



0% 0,4% 1,1% 3,1% 4,6%

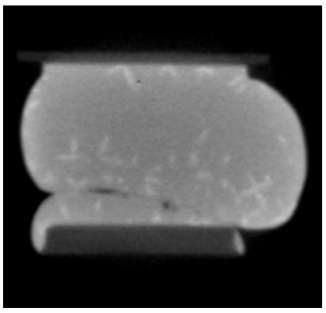


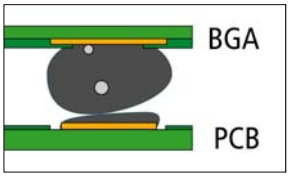

*(MPA Stuttgart)*

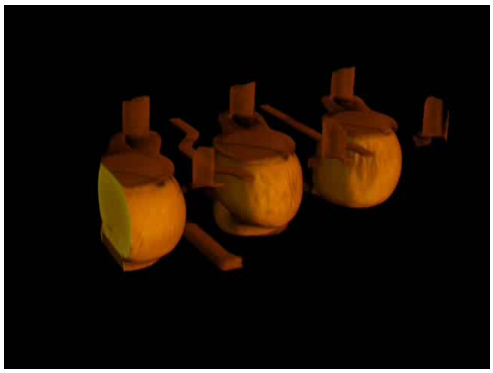




## X-ray inspection and computed tomography (CT)



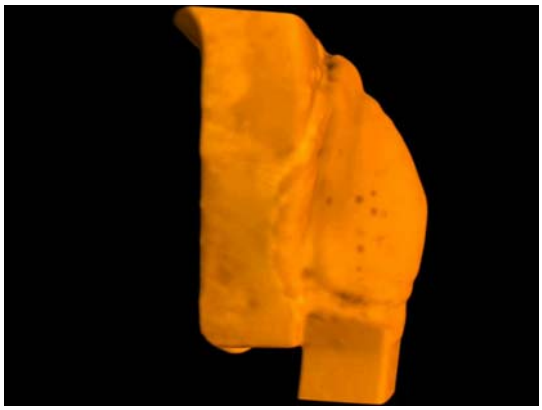


BGA solder joints (CT volume animated)

*(GE; phoenix|x-ray Systems + Services GmbH)*

## Quality assurance
## Non-destructive testing (NDT)



Laser beam weld (X-ray; CT volume animated)

*(GE; phoenix|x-ray Systems + Services GmbH)*

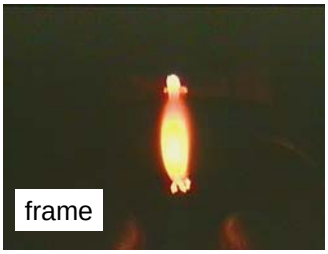


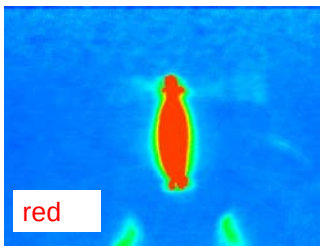


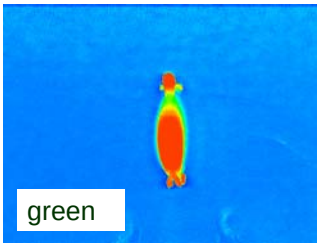


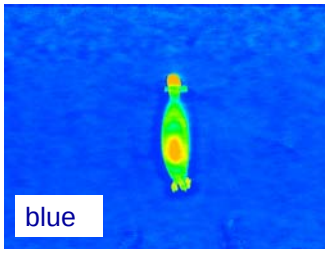
## Quality assurance
## video based process analysis

### Resistance butt welding (different colour filter)

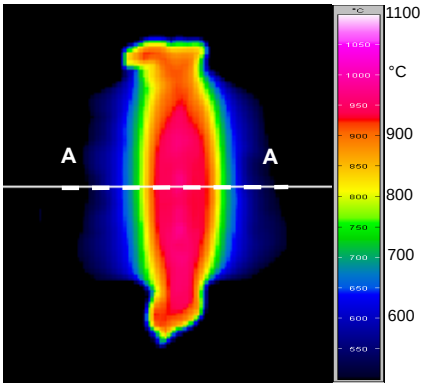


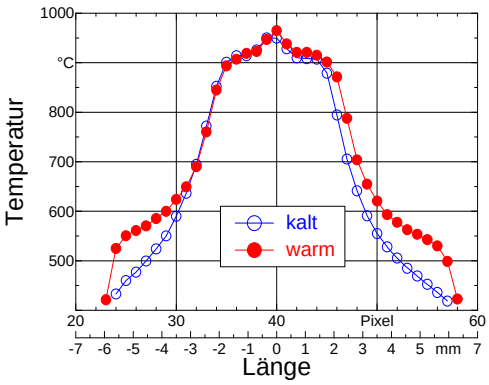



## Resistance butt welding



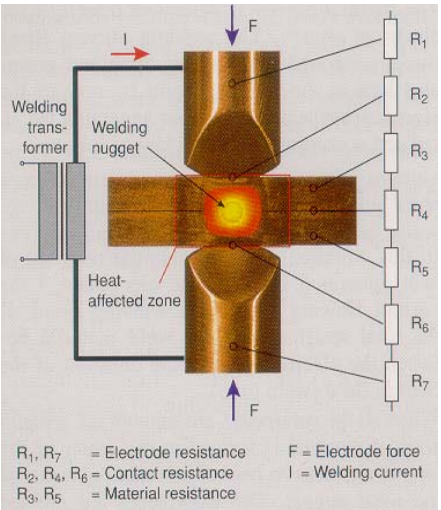

heat image

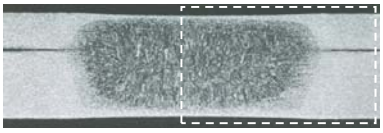


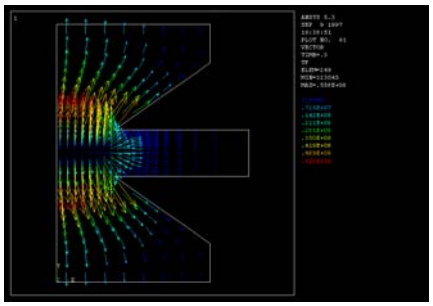

temperature distribution







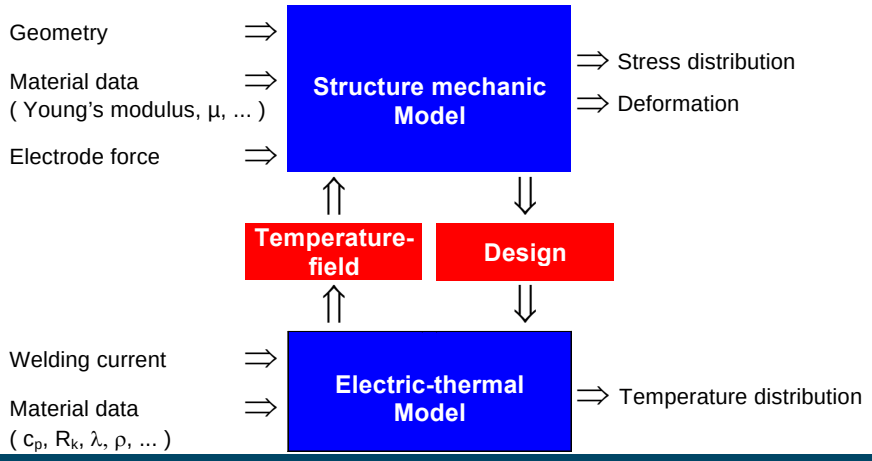


Spotwelder (1997)

Resistance spot welding (material: DC04; $t_1$=0.8mm / $t_2$=1.5 mm)

## Resistance Welding

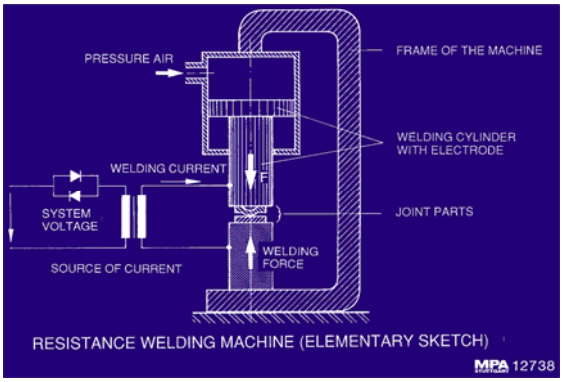
***MODEL FOR NUMERICAL ANALYSIS***

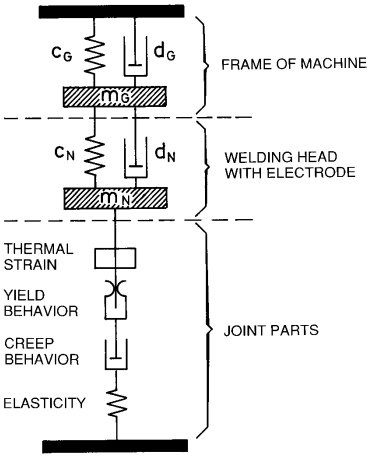






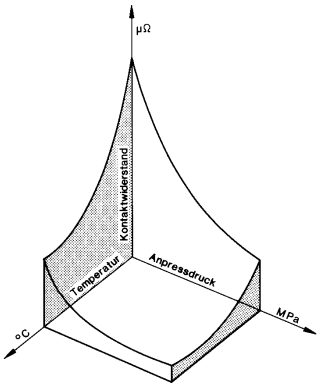

## Mechanical Model - Machine

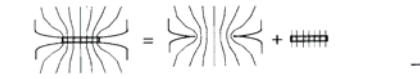


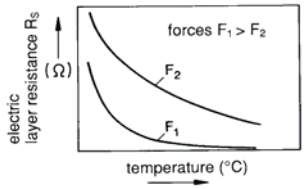



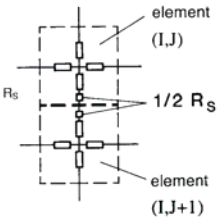

RESISTANCE WELDING MACHINE - MECHANICAL MODEL MPA 12745

## Electrical model – Contact resistance



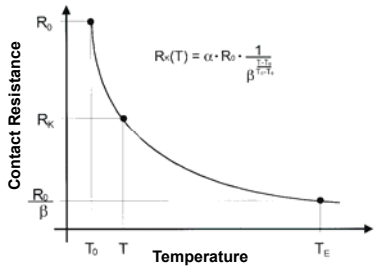

Modell for the electric contact resistance

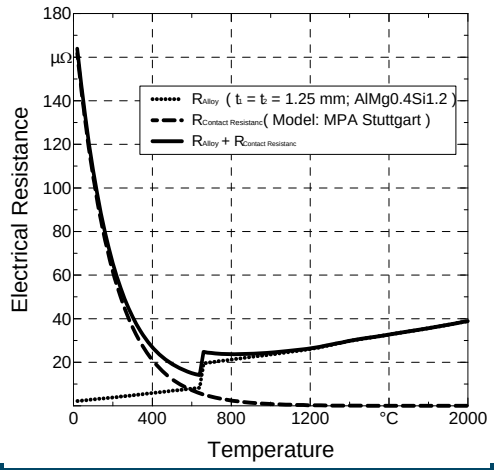
MPA 12747



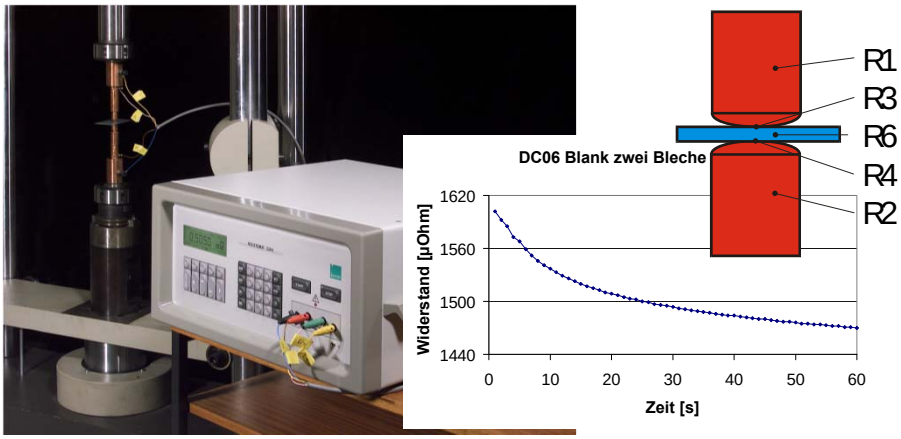


## *Database*
## *Material Resistance and Contact Resistance*



## Contact resistance



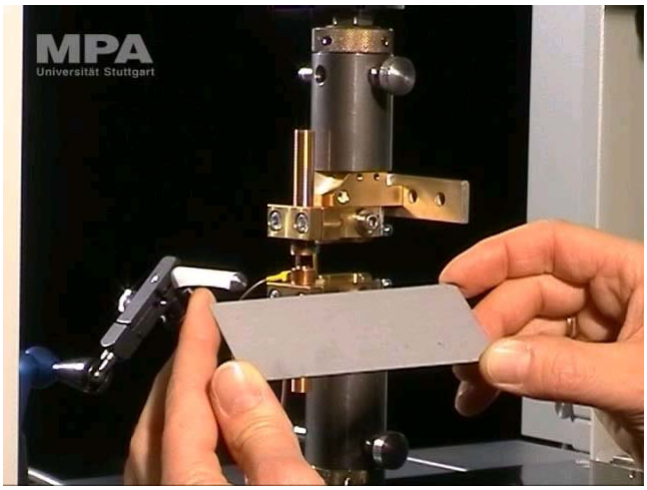

**Measuring transitent resistance - experimental setup**

*(MPA Stuttgart)*



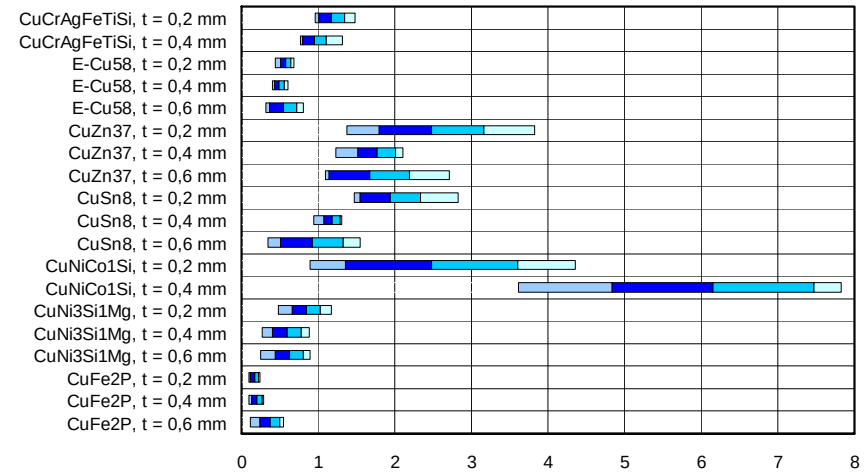


## Measurement - transition resistance




**ISO 18594**

## Transition resistance (copper alloys)




*(MPA Stuttgart)*



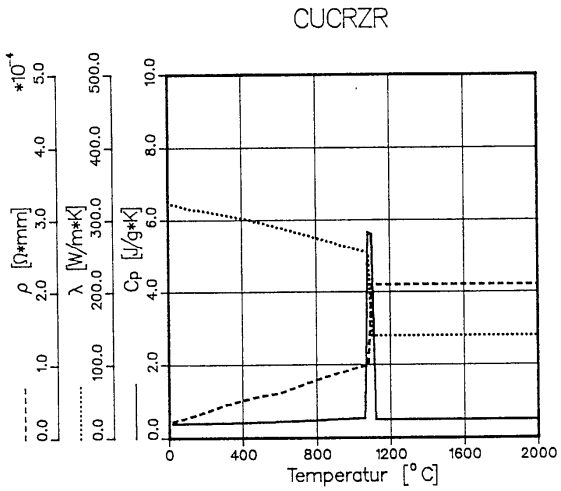


## Numerical process analysis

# Data base

# physical material properties

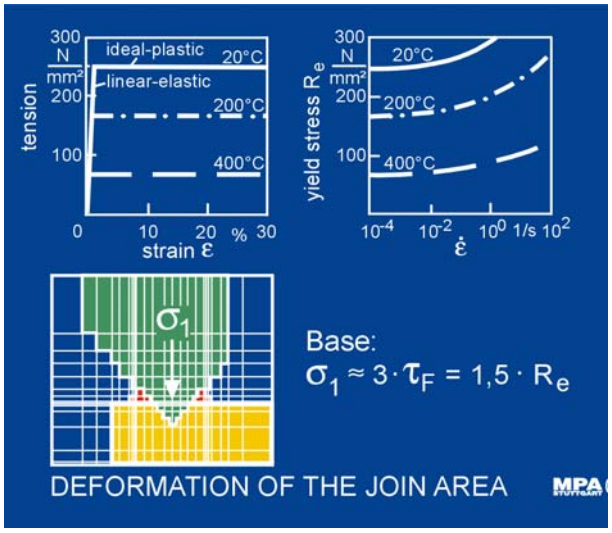
***electrical resistivity ρ***
***thermal conductivity λ***
***heat capacity $c_p$***



## Numerical process analysis

# Data base

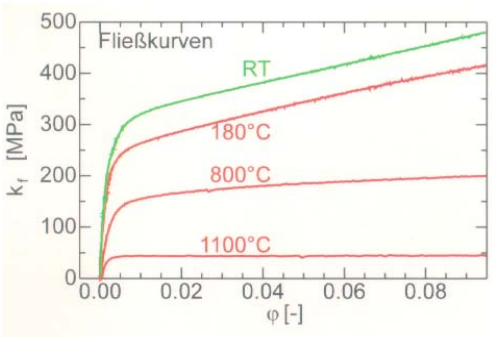
## mechanical material properties

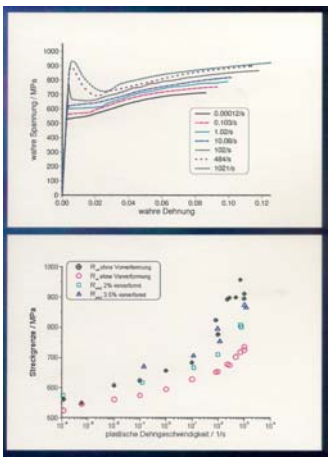







## Numerical process analysis

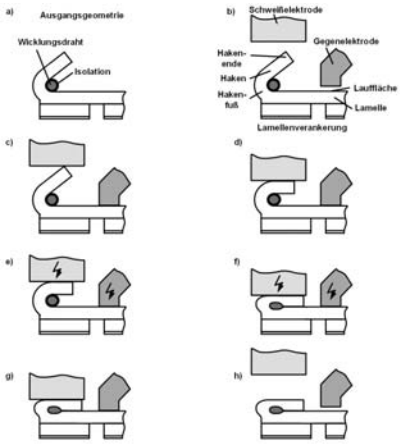


# Data base

## mechanical material properties

## Numerical process analysis
## Hot staking process



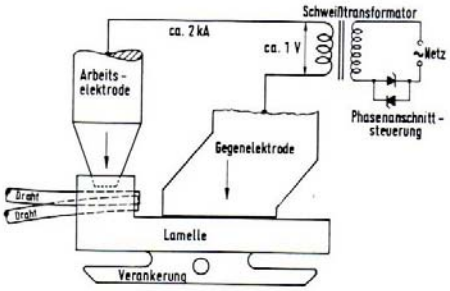

**Resistance welding of commutator segments with hook geometry**



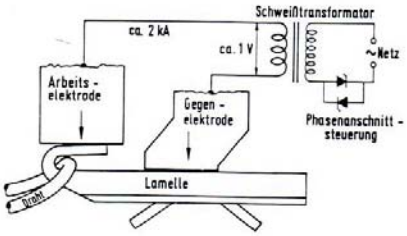
Hochschule Esslingen
University of Applied Sciences

## Numerical process analysis
## Hot staking process

### Resistance welding of commutator segments



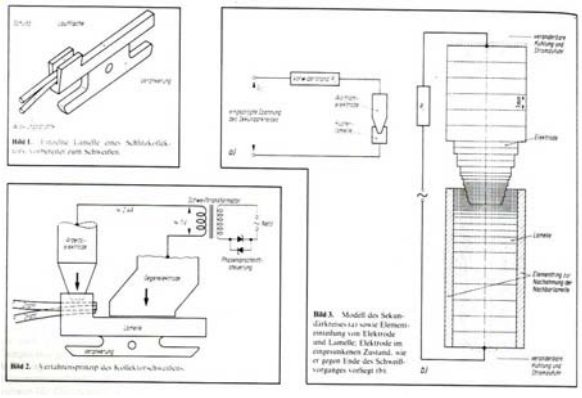

a) Schlitzkollektorverfahren




b) Hakenkollektorverfahren

**slot geometry** **hook geometry**

**1984** **R. Schwab (doctoral thesis): numerical simulation of Hot Staking process**

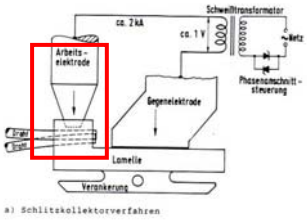


**commutator segments with slot geometry**

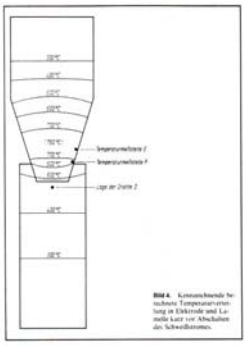




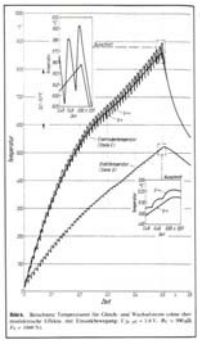
**1984** **R. Schwab (doctoral thesis): Numerical simulation of Hot Staking process**




**commutator segments with slot geometry**



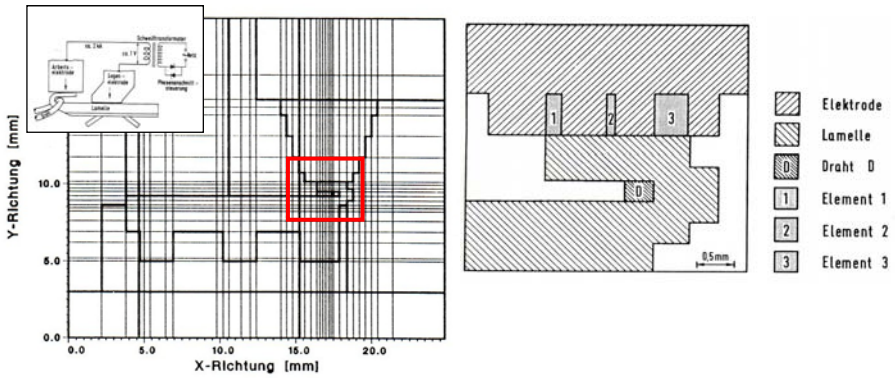
**temperature field**



**temperature-time-curve**

*(Schweißen und Schneiden, 38 (1986), Heft 8, S. 365-369)*

**1990** **P. M. Schäfer (doctoral thesis): numerical simulation of Hot Staking process**

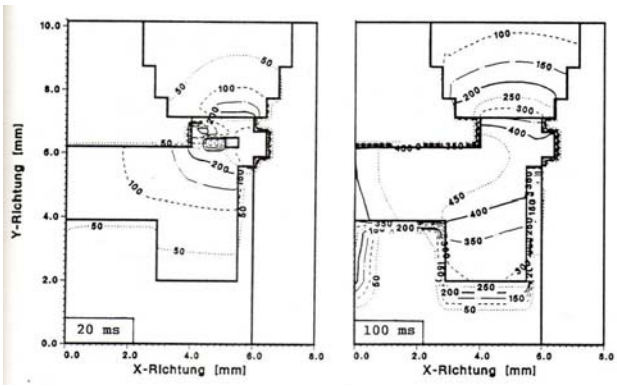



**commutator segments with hook geometry**





**1990** **P. M. Schäfer (doctoral thesis): numerical simulation of Hot Staking process**

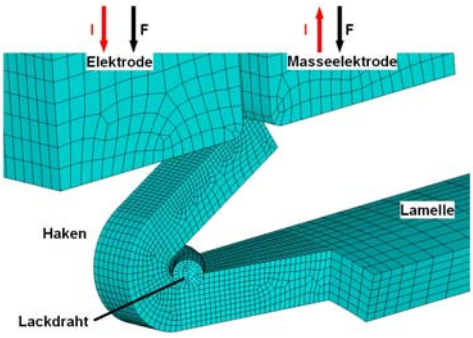


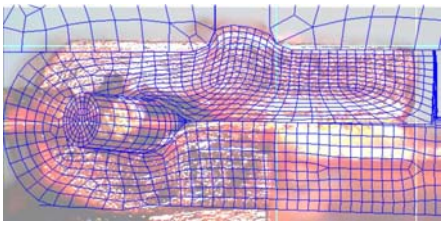

**temperature field**
(time: 20 ms and 100 ms)

*(DVS-Berichte, Band 89)* **commutator segments with hook geometry**

Hochschule Esslingen
University of Applied Sciences

## Numerical process analysis
## Hot staking process (2012)



**Resistance welding of commutator segments with hook geometry**

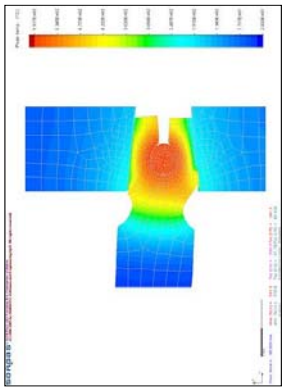
*(Lanier)*





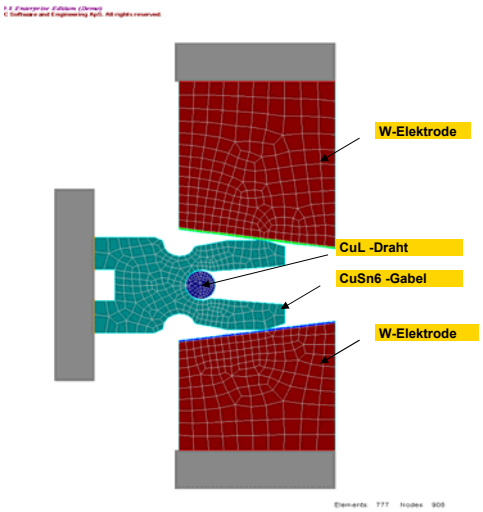
Hochschule Esslingen
University of Applied Sciences

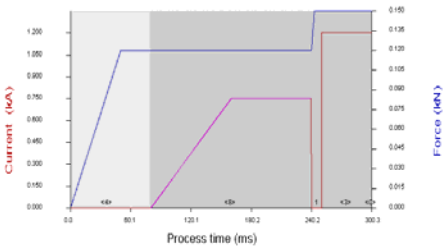
## Numerical process analysis
## electrotecnic application



**wire termination**

# Numerical process analysis electrotechnic application



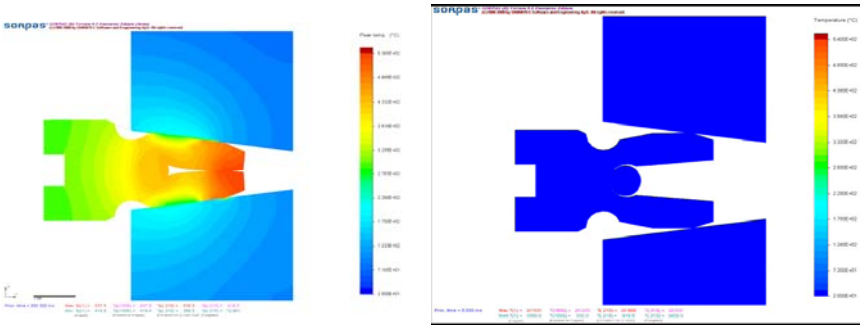

## FEM Model & Process

*(Dötzer)*





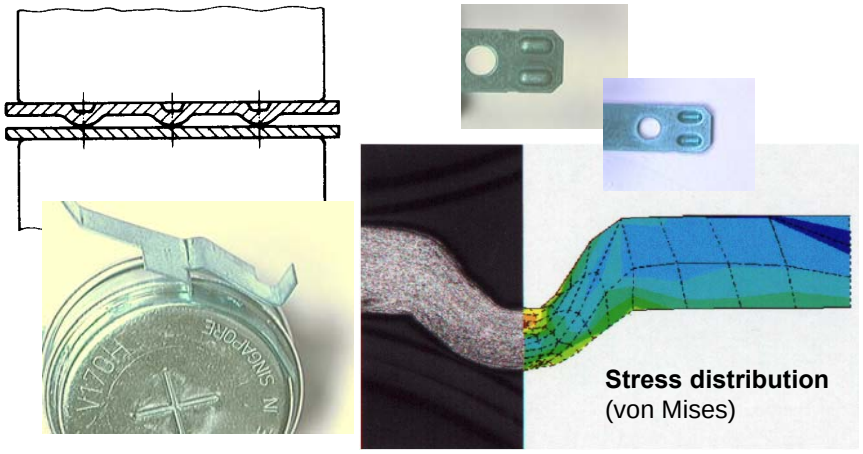
# Numerical process analysis electrotechnic application



*(Dötzer)*

## Numerical process analysis electrotechnic application

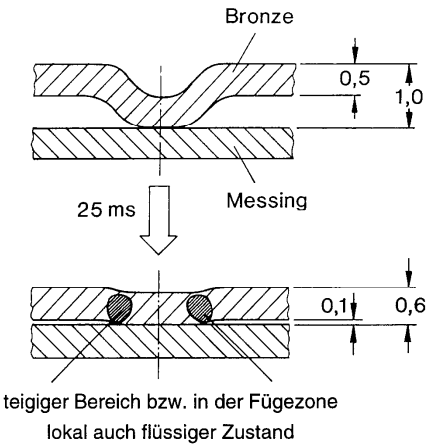
**Projection welding**

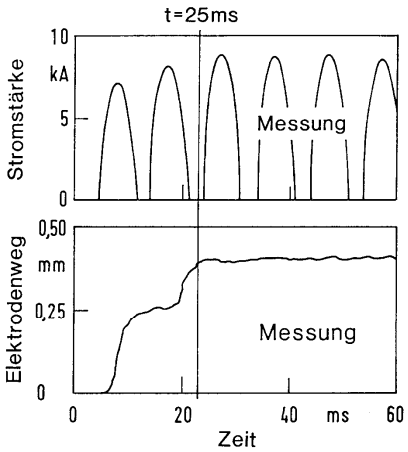





Hochschule Esslingen
University of Applied Sciences

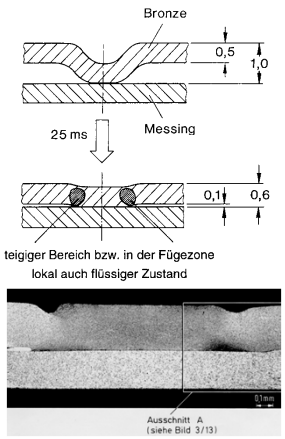
## Numerical process analysis electrotechnic application

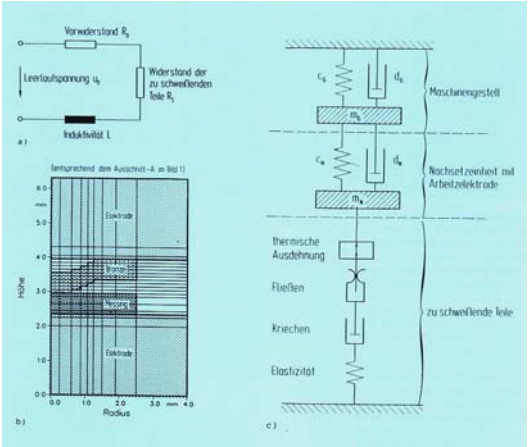



*(Kußmaul, Blind, Zeng, Greitmann, Schäfer, 1991)*

## Numerical process analysis electrotechnic application



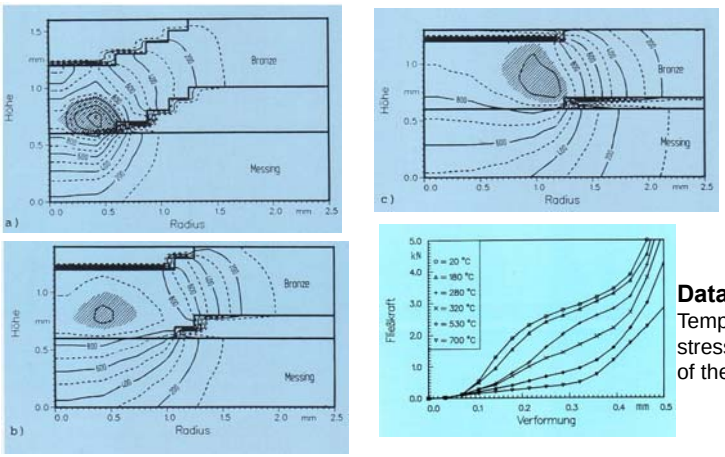

**Process & mechanical model**

*(Kußmaul, Blind, Zeng, Greitmann, Schäfer, 1991)*





## Numerical process analysis electrotechnic application







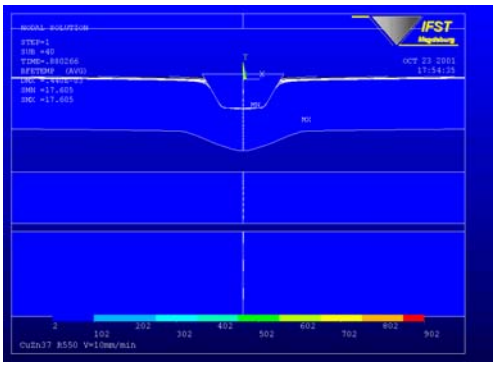
**Database:**
Temperature-dependent stress-strain behaviour of the used projection

**Calculated projection deformation and temperature distribution**

*(Kußmaul, Blind, Zeng, Greitmann, Schäfer, 1991)*

## Numerical process analysis electrotechnic application

**2001** **Alexei Vichniakov (doctoral thesis): numerical simulation of projection welding**



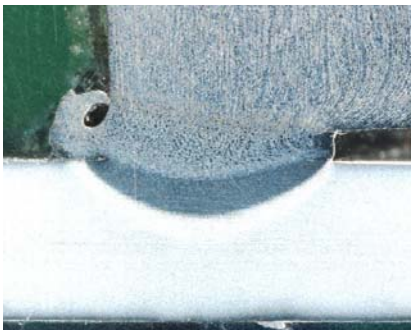

**calculated movement and temperature distribution**

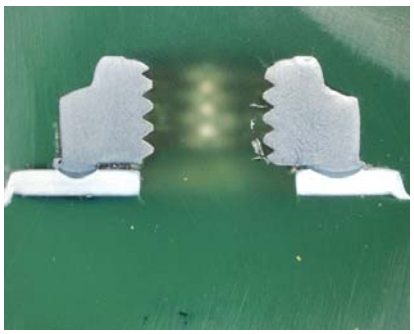
*(Vichniakov, Herold, Greitmann, Roos, 2002 in Mathematical modelling of the weld phenomena )*





## Numerical process analysis projection welding of srew nuts

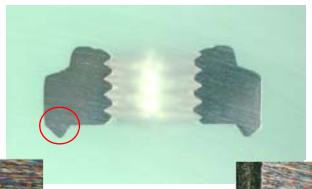




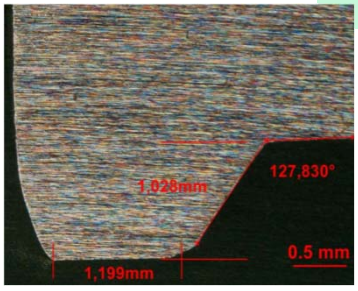
**Projection welding: srew nuts onto high strength steel sheet**

*(Bschorr, Cramer, SLV München NL der GSI mbH)*

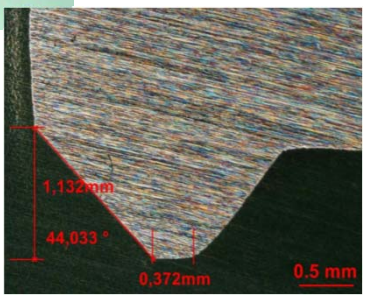
## Numerical process analysis projection welding of srew nuts



old




new




**Optimization of srew nut geometry**

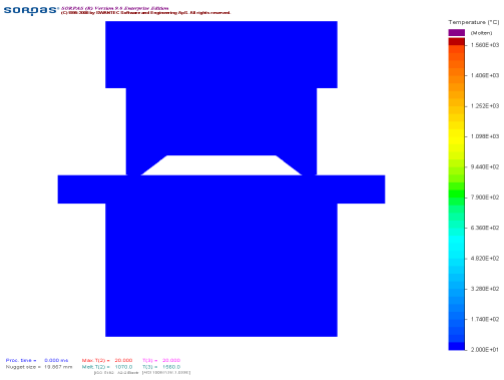
*(Bschorr, Cramer, SLV München NL der GSI mbH)*



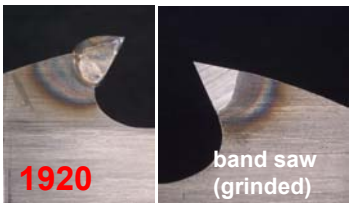


## Numerical process analysis projection welding

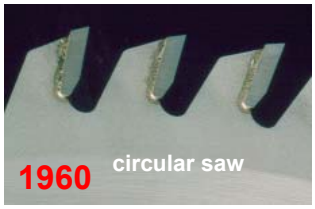
- Square nut welding



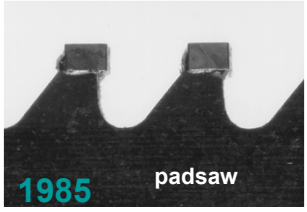
## Numerical process analysis
## Carbide tipped saw blade



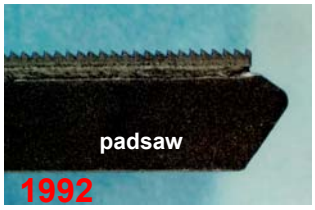

stellite hard facing




Brazing (CuAg solder)




resistance welding



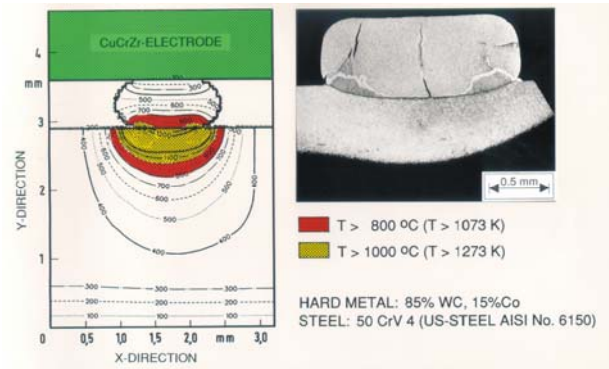

Laser beam welding





## Numerical process analysis
## Carbide tipped tools (1990)

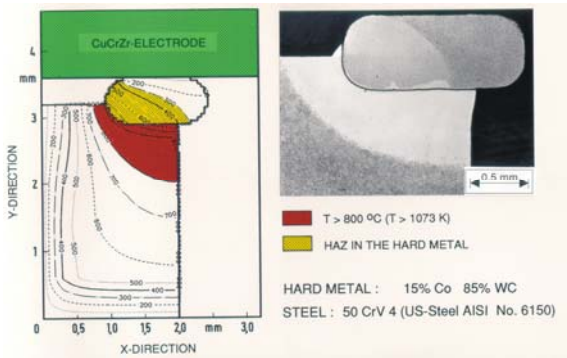
**1990** **Martin J. Greitmann (doctoral thesis)**




Comparison of calculated temperature field and metallographic cut of a hard metal / steel weldment

## Numerical process analysis
## Carbide tipped tools (1990)

**1990** **Martin J. Greitmann (doctoral thesis)**

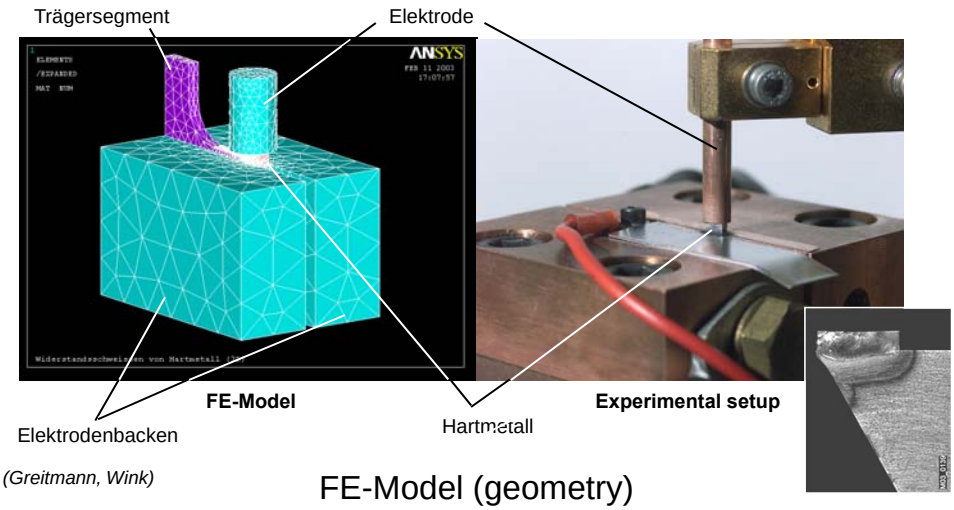



Comparison of calculated temperature field and metallographic cut of a hard metal / steel weldment





## Numerical process analysis
## Carbide tipped band saw (2000)



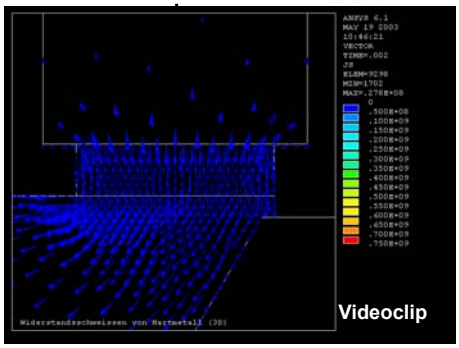

*(Greitmann, Wink)*

FE-Model (geometry)

## Numerical process analysis
## Carbide tipped band saw (2000)

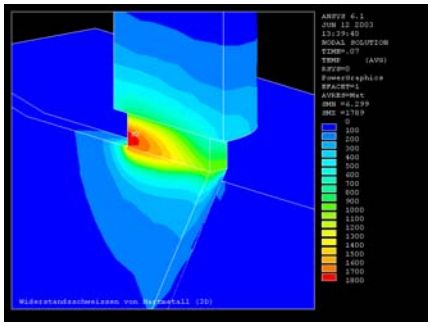
**Current distribution**

A




A

**Temperature field**



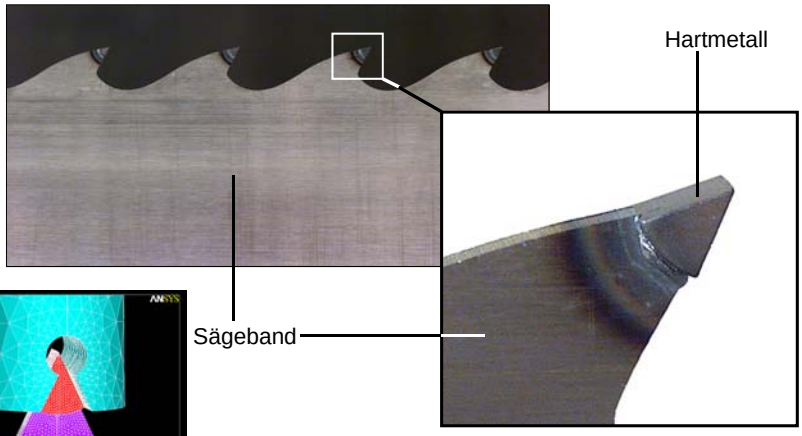
time: 70 ms

*(Greitmann, Wink)*





## Numerical process analysis
## Carbide tipped band saw (2000)




**Carbide tipped saw band**

*(Greitmann, Wink)*

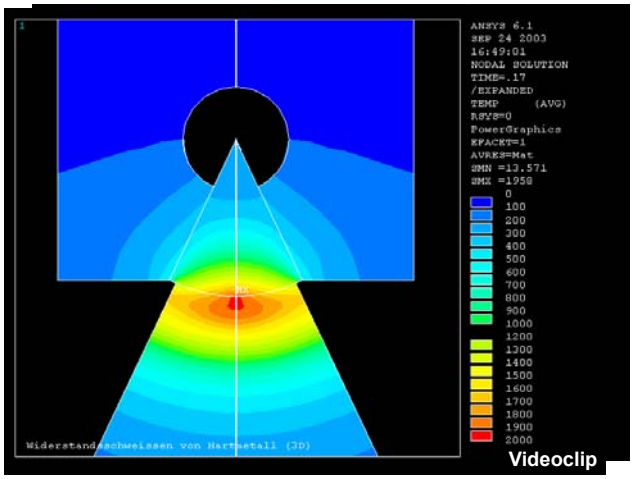
Hochschule Esslingen
University of Applied Sciences

## Numerical process analysis
## Carbide tipped band saw (2000)

**Temperatur-bereich 0°C bis 2000 °C**

**Konturabstand 100 °C**

**Realtime-Bildfolgezeit 5 ms**




**Videoclip**

**Längsschnitt**

*(Greitmann, Wink)*

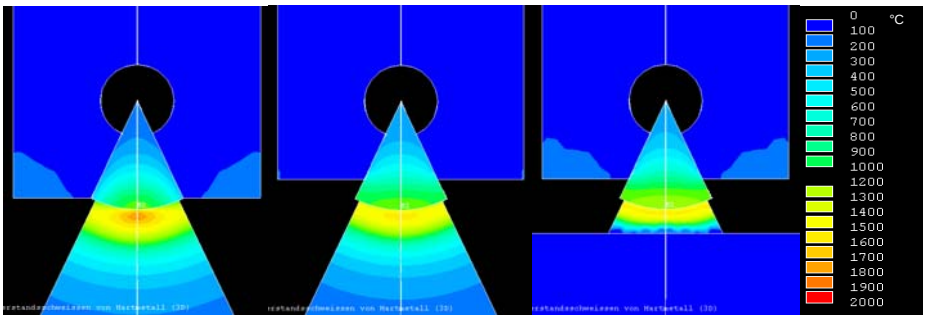




Hochschule Esslingen
University of Applied Sciences

## Numerical process analysis
## Carbide tipped band saw (2000)

**Temperature distribution for a max. temperature of aprox. 1500 °C in the welding zone**



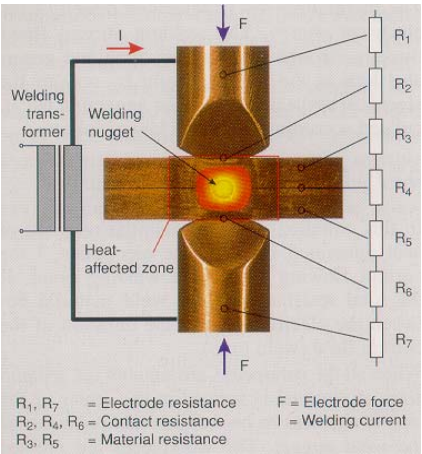

**Hartmetallüberstand: 0 mm**
**Sägeblattüberstand: 7,65 mm**
**Zeitpunkt: 145 ms**

**Hartmetallüberstand: 0,8 mm**
**Sägeblattüberstand: 7,65 mm**
**Zeitpunkt: 130 ms**

**Hartmetallüberstand: 0,8 mm**
**Sägeblattüberstand: 1,0 mm**
**Zeitpunkt: 145 ms**

*(Greitmann, Wink)*

## Numerical process analysis resistance spot welding



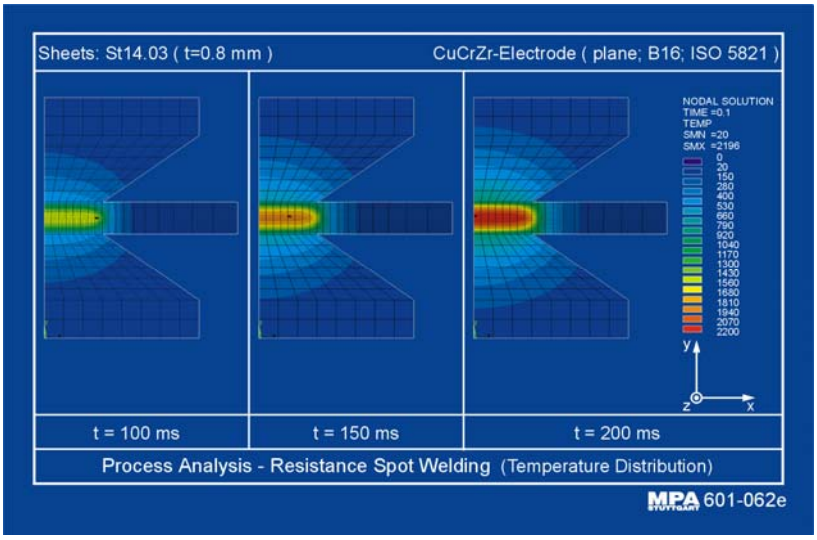

***APPLICATION***

***Spot Welding***



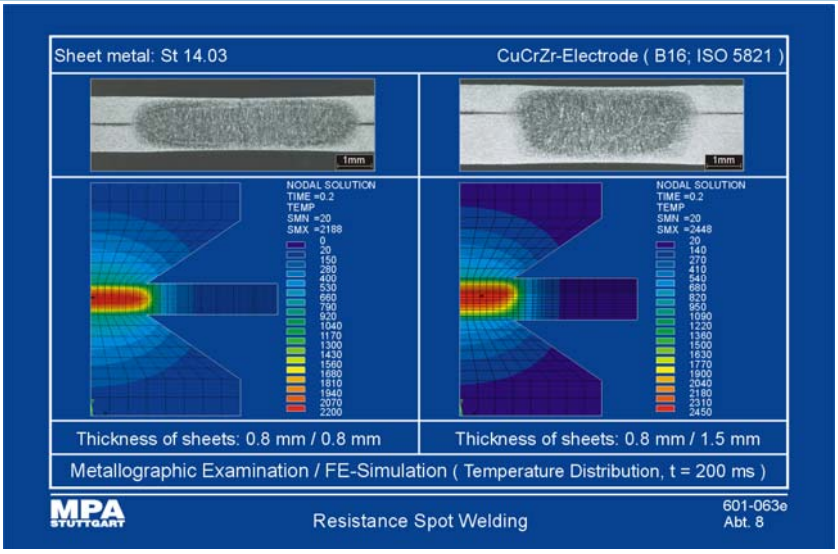


## Numerical process analysis resistance spot welding (1996)



Hochschule Esslingen
University of Applied Sciences

## Numerical process analysis resistance spot welding (1996)

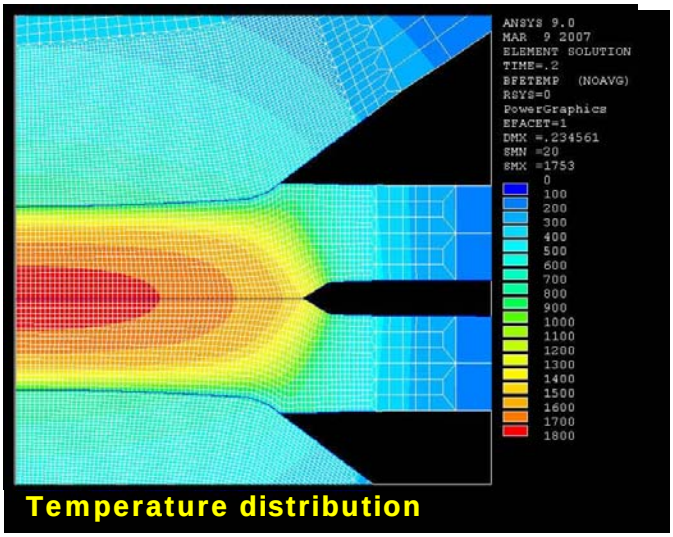



*Example: Variable sheet thickness*

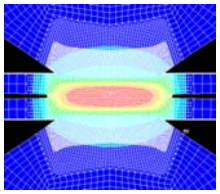


Hochschule Esslingen
University of Applied Sciences

## Numerical process analysis resistance spot welding (2007)



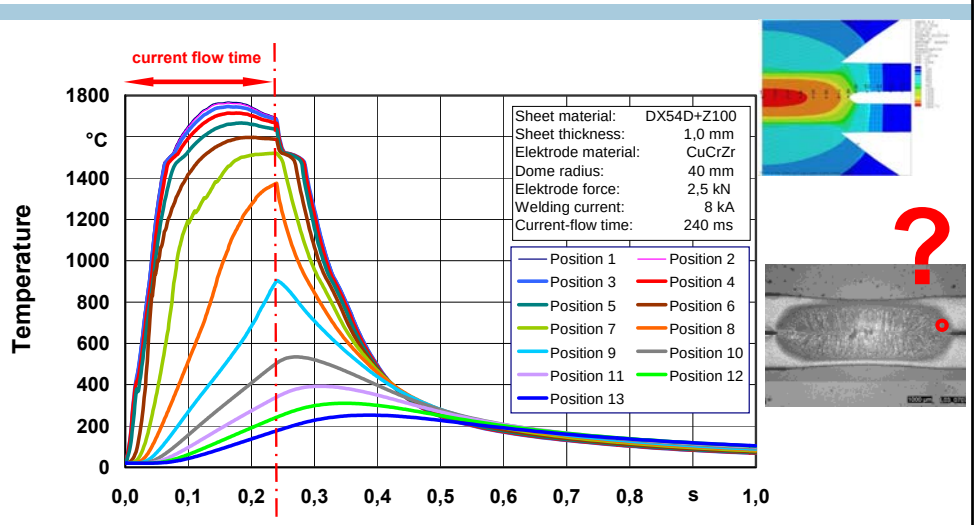

**Temperature distribution**



*(Greitmann, Wink)*

Hochschule Esslingen
University of Applied Sciences

## Numerical process analysis resistance spot welding (2007)






*(Greitmann, Wink)*

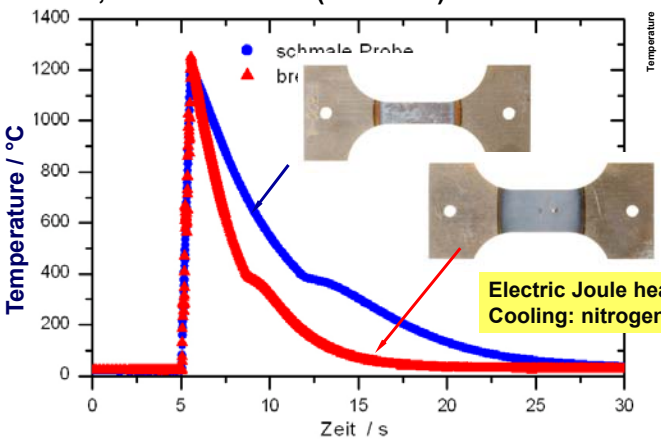
**local temperature–time history**

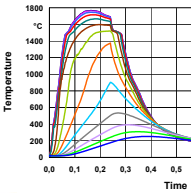


Hochschule Esslingen
University of Applied Sciences

## Numerical process analysis resistance spot welding

**Experimental thermal simulation**
**1250 °C / 0.5 s, Steel: HCT700T (TRIP 700)**



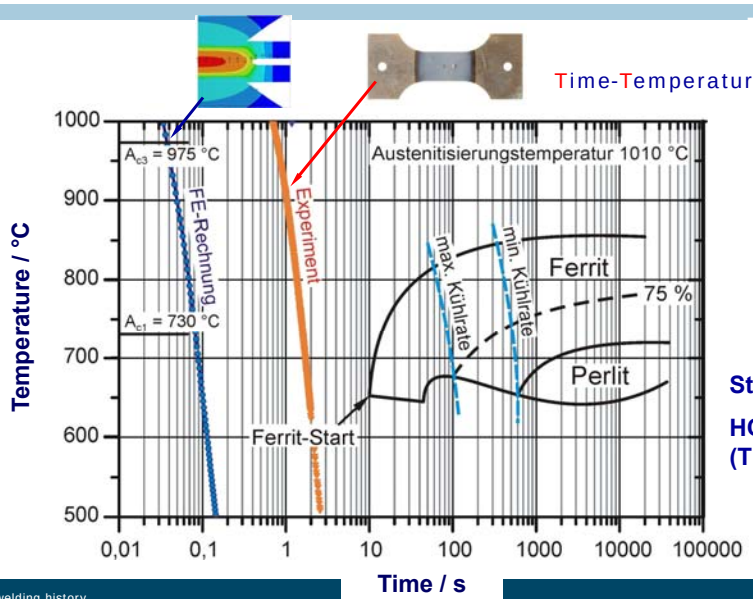

**Electric Joule heating: AC current**
**Cooling: nitrogen cover gas**

*(Greitmann, Wink, Kießling)*

**Time /s**

## Numerical process analysis resistance spot welding

Time-Temperature-Transformation




**Steel:**

**HCT700T (TRIP 700)**

*(Greitmann, Wink, Kießling)*

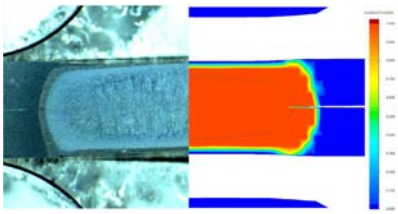


Hochschule Esslingen
University of Applied Sciences

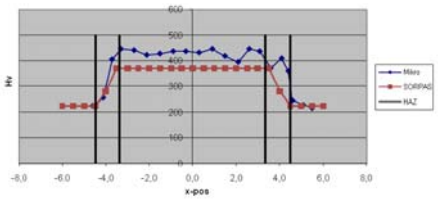
Numerical process analysis resistance spot welding

### Spot welding 1.5 mm DP600 steel sheets

Microstructure and hardness distribution



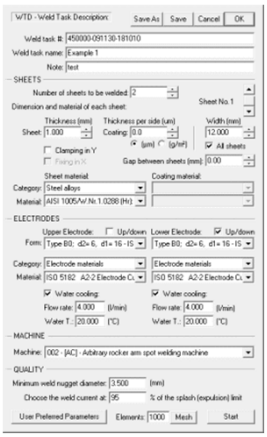
Macrograph of real weld comparing to simulated weld nugget and martensite distribution

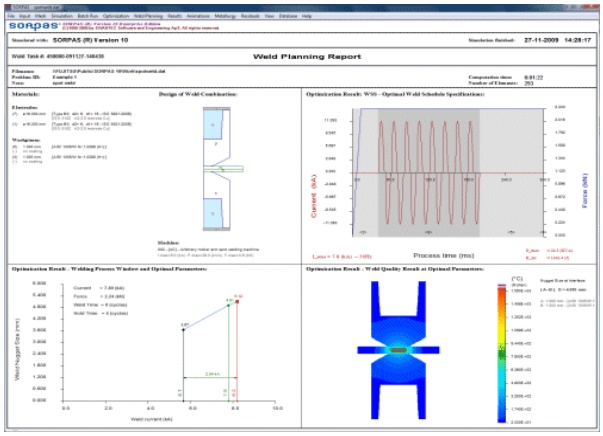


Measured micro hardness comparing to simulated hardness near the weld nugget

SORPAS®

## Weld Schedule Specifications with optimal welding parameters










## *Use of numerical Analysis*

- Optimization of joint geometry
- Weldability of different materials
- Weldability of metallic coatings
- Optimization of joining parameters
  *(tool geometry, welding current and electrode force)*

## Education and Training

**1910's** **Training of welders**
Sixteen courses of welding at various institutions in the German empire, at nearly more than 100 locations.
Also England & France had established government welding schools

**1915** Army Welding School Kenosha, Wisconsin

Fig. 10.1: Army Welding School Kenosha, Wisconsin, circa 1915

Fig. 10.6: Chicago Welding Institute, 1916

*(DVS, WELDING - A JOURNEY TO EXPLORE ITS PAST)*





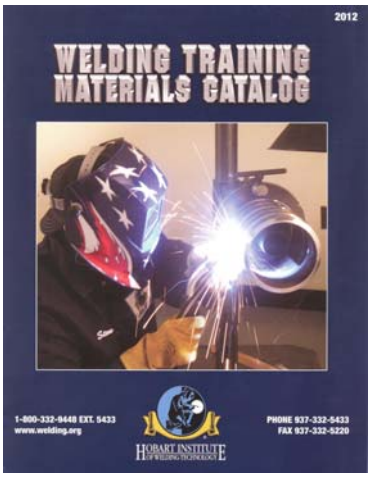
## Education and Training

**1925** **Hobart Brothers Company**
first „Arc Welder"

**1930** **First 80-page training booklet**
„Electric Arc Welding"
by Wilbur J. **Chaffee**


Fig. 10.10 Electric Arc Welding by Wilbur J. Chaffee, Hobart Brothers Company

*(WELDING - A JOURNEY TO EXPLORE ITS PAST)*




*(Hobart Institute of Welding Technology)*

## Education and Training

### Welding simulation

*(Lincoln Electrin)*





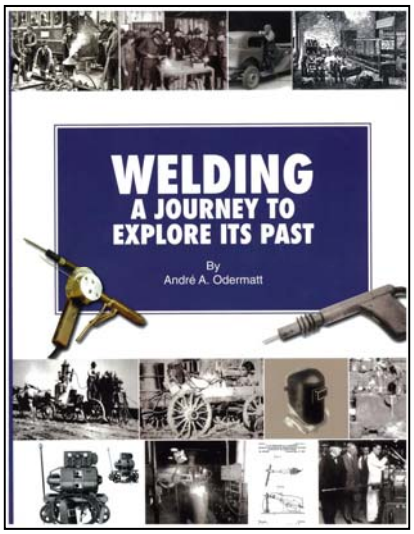
## Welding through the Ages


**1897 German Welding Society (DVS)**

**1919 American Welding Society (AWS)**
was founded as a multifaceted, nonprofit organization with a goal to advance the science, technology and application of welding and related joining disciplines

*(DVS, AWS)*

## Welding through the Ages




***An efficient welding technology combined with best trained welders will open the door for going green.***

***Thank you for your attention !***





## Welding through the Ages
## References

/1/ ODERMATT, André, A.:
WELDING – A JOURNEY TO EXPLORE ITS PAST.
Hobart Institute, www.welding.org

/2/ PUSCHNER, M.:
5 Jahrtausende Schweißen – Eine Frühgeschichte der Schweißtechnik.
ISBN: 978-3-87155-714-9, DVS Media GmbH, Deutscher Verlag für Schweißtechnik GmbH, Düsseldorf (1986)

/3/ GOLDMANN, Felix:
Die elektrische Widerstandschweißung im Lichte der Metallographie.
Dissertationsarbeit, Technische Hochschule München, Druck von Friedr. Vieweg & Sohn AG, Braunschweig (1930)

/4/ DVS:
Jubiläumsband „100 Jahre DVS“ DVS Media GmbH, Artikelnummer: 600050, Deutscher Verlag für Schweißtechnik GmbH, Düsseldorf (1997)

/5/ DE FODOR, Etienne: Die elektrische Schweissung und Löthung – Nachdruck der 1892 erschienenen Originalausgabe.
ISBN 13: 978-3-87155-703-3, DVS Media GmbH, Deutscher Verlag für Schweißtechnik GmbH, Düsseldorf (1980)

/6/ PETER, H.-J.:
Löten – eine „Ur“-alte Geschichte.
Schweißen und Schneiden Bd. 57 (2005) No. 9, p. 512-520, DVS Media GmbH, Düsseldorf

/7/ BEHNISCH, Hellmuth & AICHELE Günter:
Die Schweißtechnik im Wandel der Zeiten.
ISBN: 978-3-87155-794-1, DVS Media, Deutscher Verlag für Schweißtechnik GmbH, Düsseldorf (2006 )