Simulation of electromagnetically formed joints

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IWU

ICHSF2012 INTERNATIONAL CONFERENCE ON HIGH SPEED FORMING

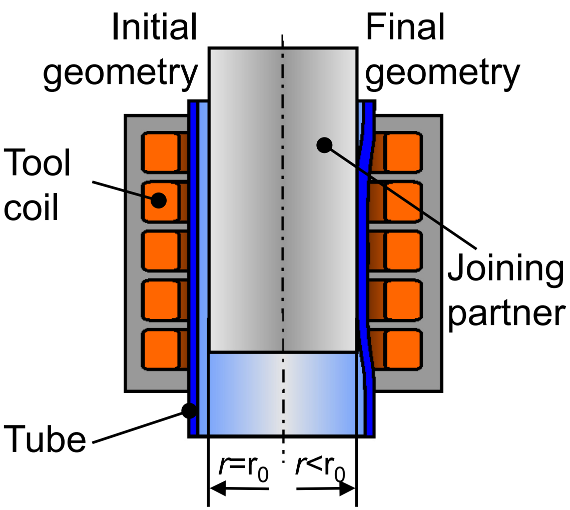
AGENDA

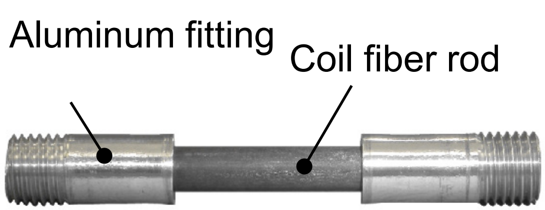
- Introduction: joining by electromagnetic forming
- Simulation strategy and modeling
- Numerical joint analysis
- Experimental verification
- Summary: numerical joint design

Joining by EMF – Joining mechanisms

Interference-fit

Elastic-plastic bracing

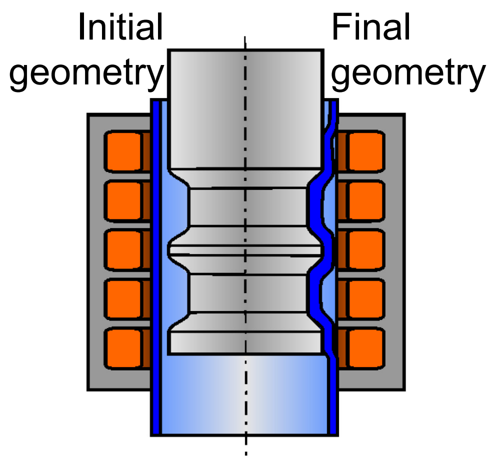




Source: IUL

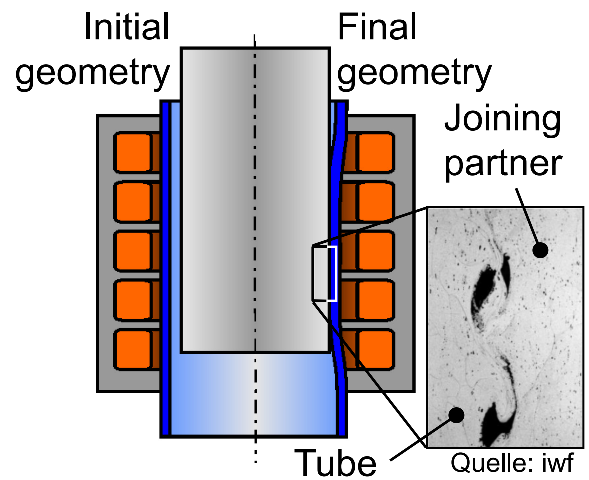
Form-fit

Formation of undercuts



Metallic bonding

Cold welding



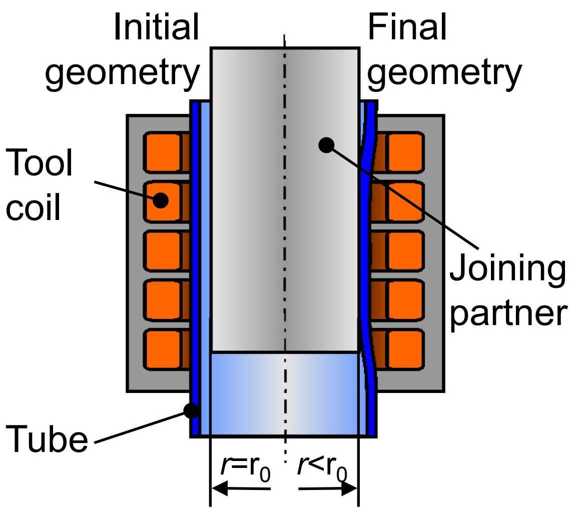
Magnetic pulse welding of sheets aluminum and steel

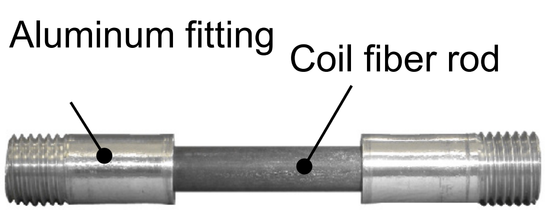
Source: PSTproducts

Joining by EMF – Joining mechanisms

Interference-fit

Elastic-plastic bracing





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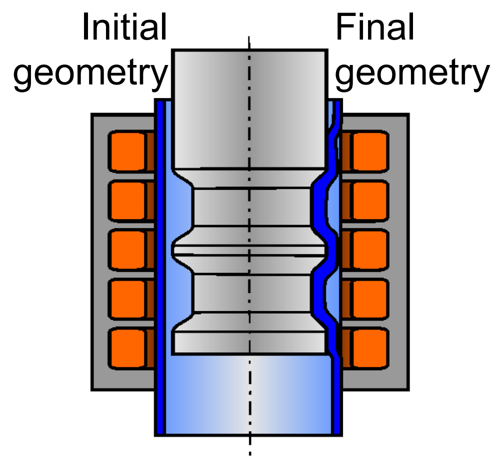


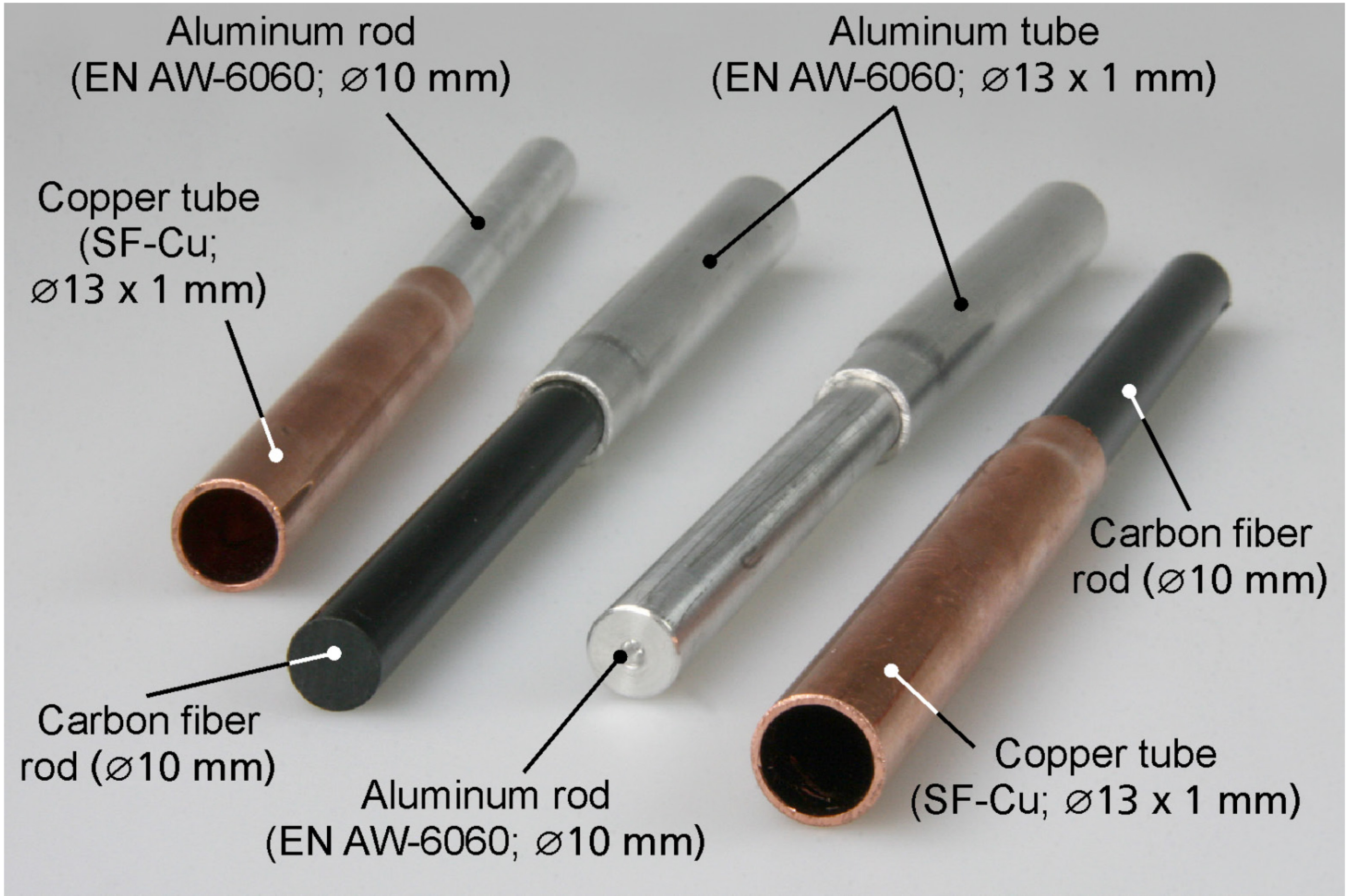
Metallic bonding

Applicable for **metal-metal joints** only.

Requires extremely **high energy.**

Aprupt failure of the joint.

Joining by electromagnetic compression – Exemplary material combinations



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Joining by EMF – Joining mechanisms

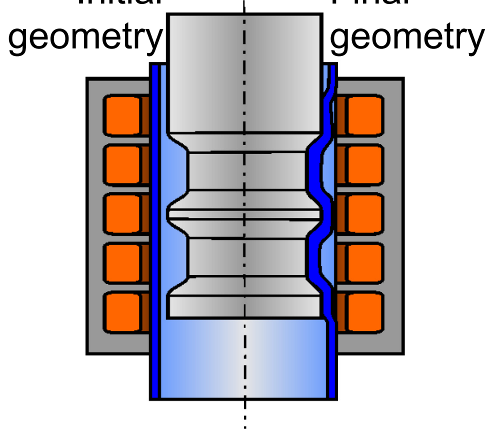
Interference-fit

Joint strength is very **sensitive to part cleanliness**.

High joint strength might require **long joining area**.

Form-fit

Formation of undercuts



Metallic bonding

Applicable for **metal-metal joints** only.

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Abrupt failure of the joint.

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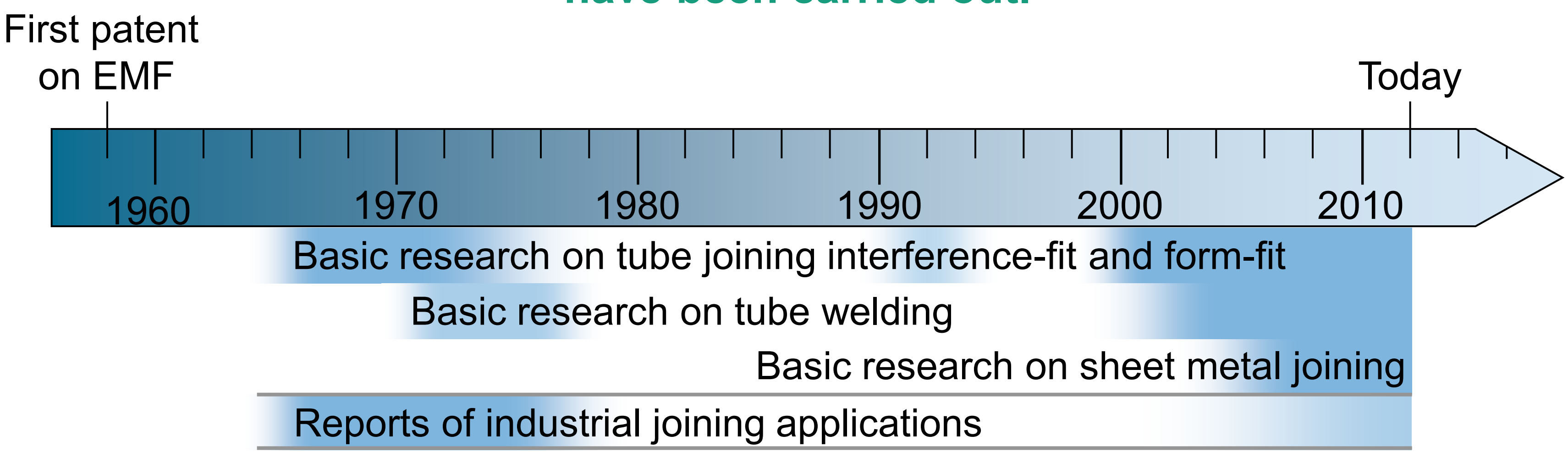
Historical development of joining by electromagnetic forming

Numerous studies focusing on the analyses of joining by EMF have been carried out.



General correlations have been identified…

…but…

…still no explicite and verified tools for designing specific electromagnetic joining applications exist.

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Numerical modeling

Input variables

Workpiece, tools

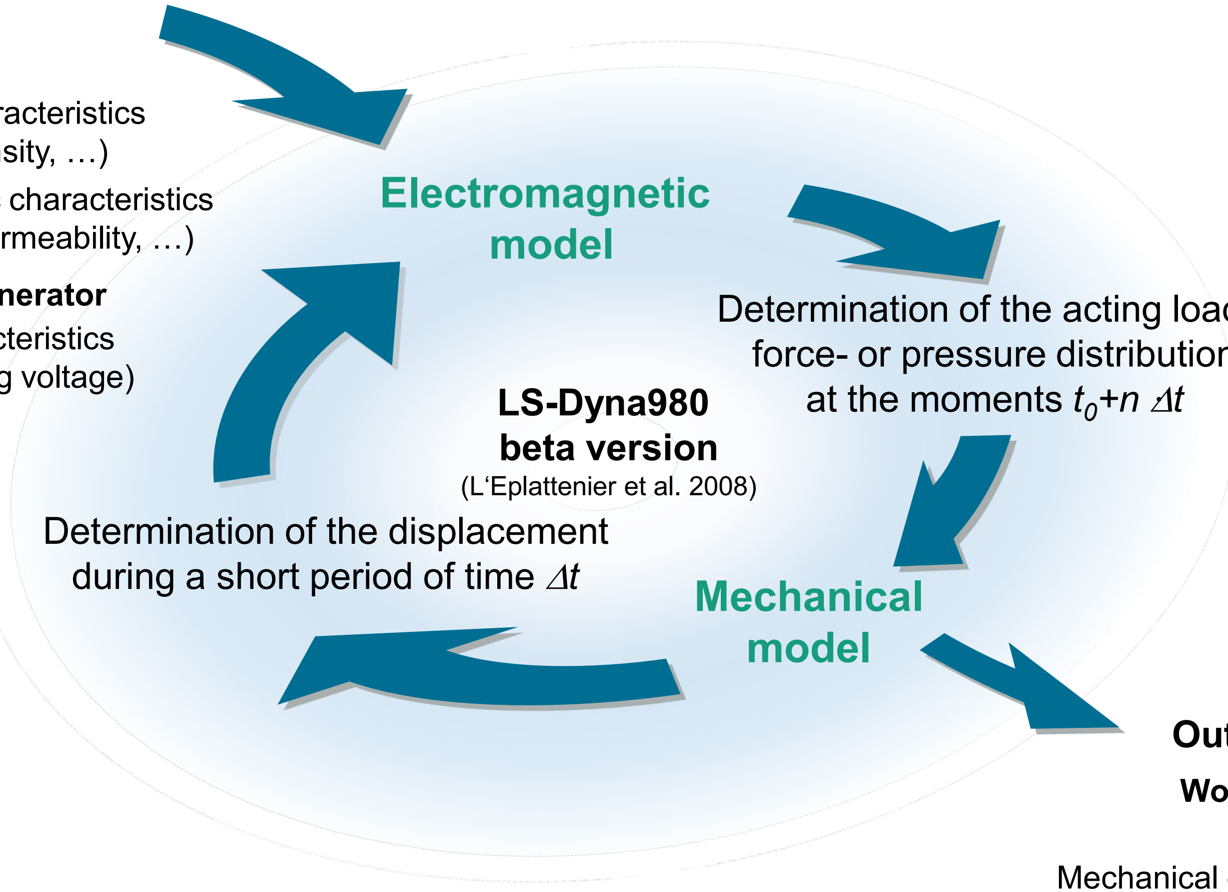
Geometry

Mechanical characteristics
(flow curve, Density, …)

Electromagnetic characteristics
(conductivity, permeability, …)

Pulsed power generator

Electrical characteristics
(C, L_i, R_i, loading voltage)



Output variables

Workpiece, tools

Geometry

Mechanical characteristics
(displacement, force, pressure, strain, strain rate, …)

Electromagnetic characteristics
(magnetic fields, current density distribution, …)

Exemplary joining task and regarded cross section geometries

Tubular joining partner

Material:	C35
Outer diameter:	42.4 mm
Wall thickness	3.2 mm

Pulsed power generator

Capacitance:	330 µF
Inner inductance:	0.15 µH
Inner resistance:	5 mΩ

Tool coil

Diameter:	102.4 mm
Length (winding):	120 mm
Number of turns:	6

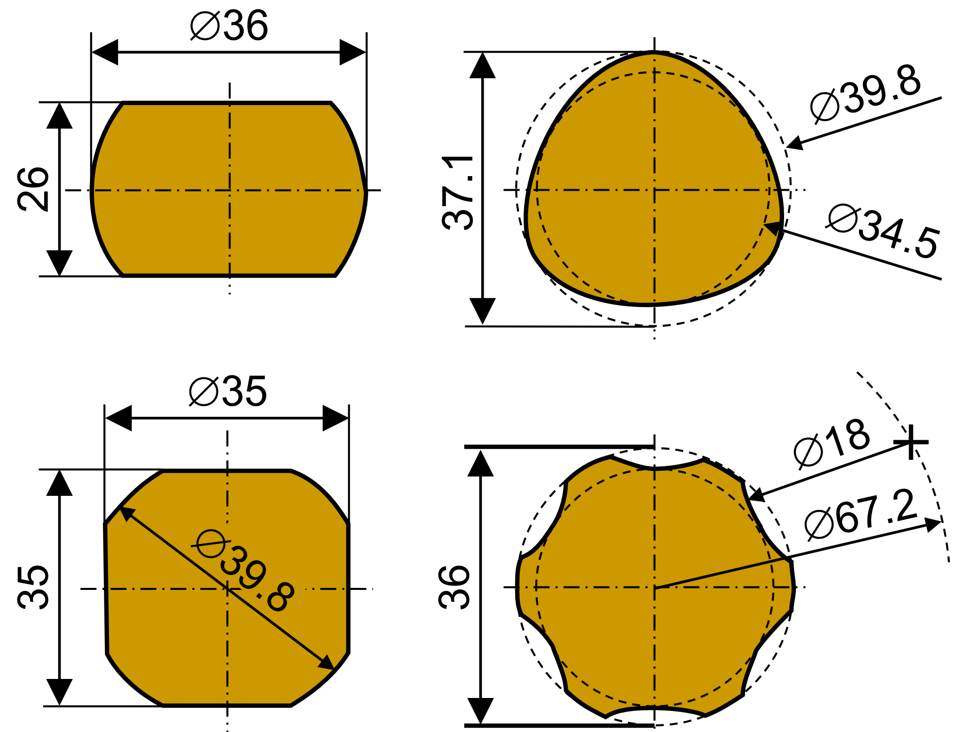
Fieldshaper

Length of con-centration zone:	35 mm
Diameter of con-centration zone:	44.9 mm

Shaft

Material: C45

Regarded cross section geometries:



Modeling of the exemplary joining task – Geometrical setup

Tubular joining partner

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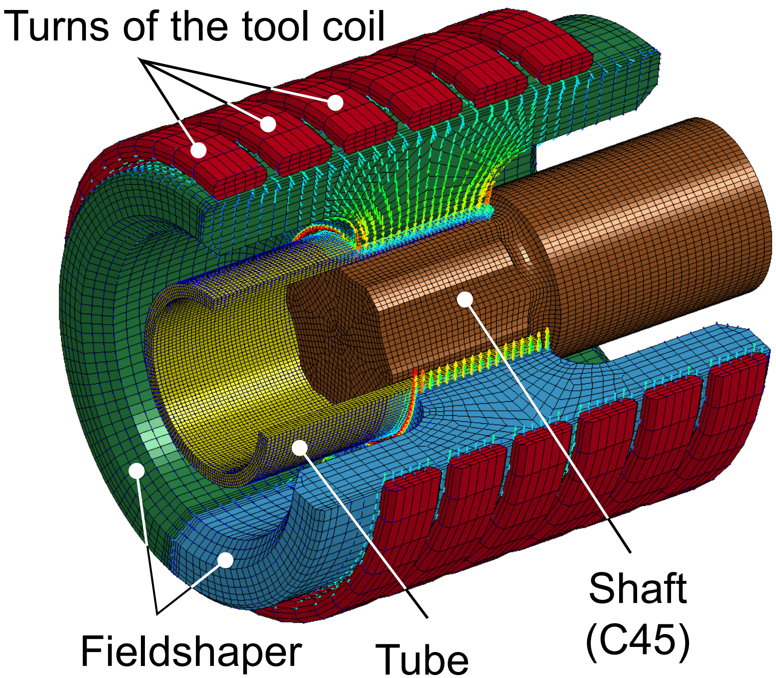
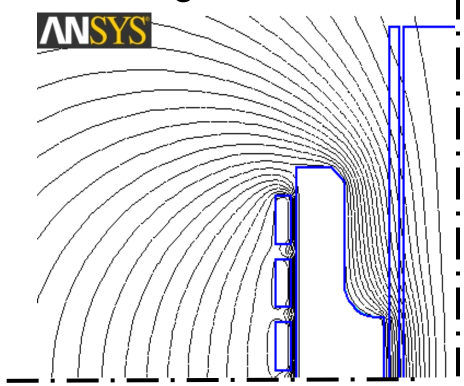


Number of nodes:	49,000
Number of elements:	171,000 (FEM)
	35,000 (BEM)

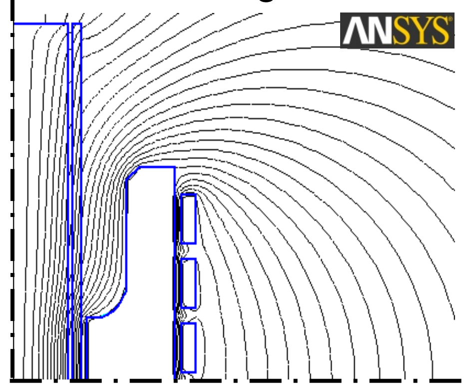
Material modeling

Magnetic field intensity

linear magnetic behavior

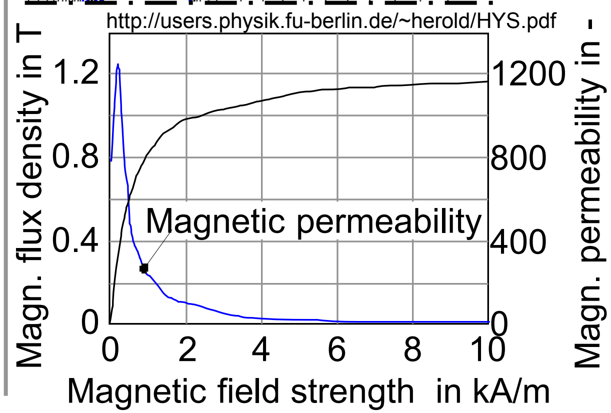


nonlinear magnetization

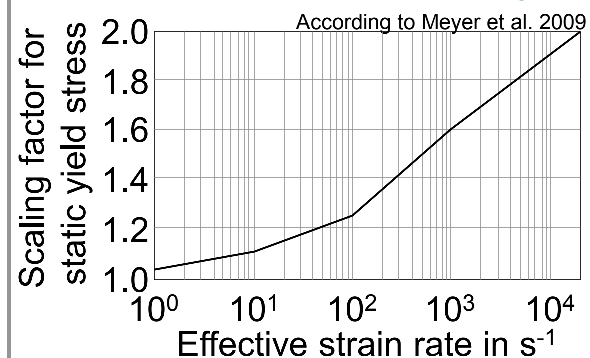


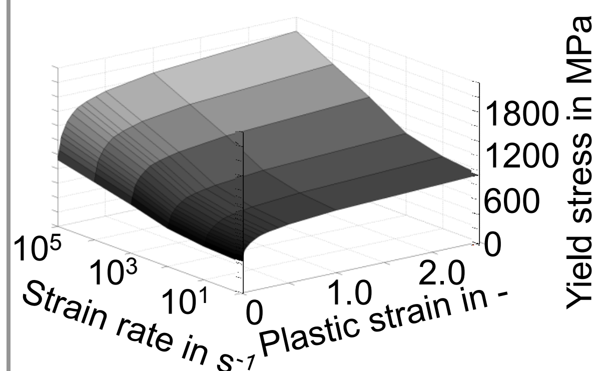
μ=const=1

Typical for non-ferromagnetic materials as aluminum, copper, etc.



Strain rate dependency





Material modeling

Magnetic field intensity

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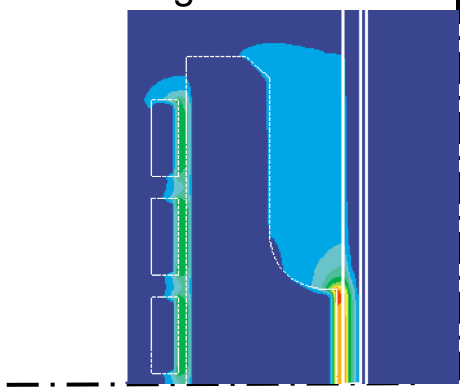
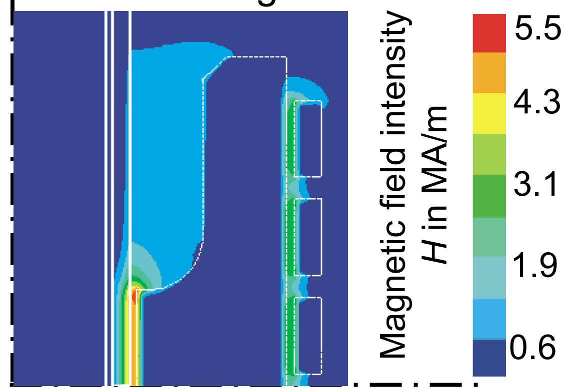


nonlinear magnetization



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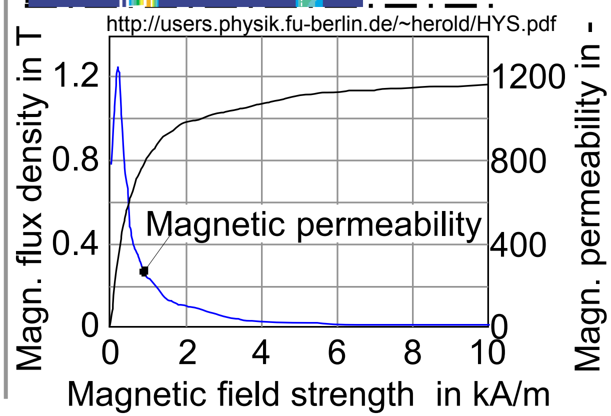
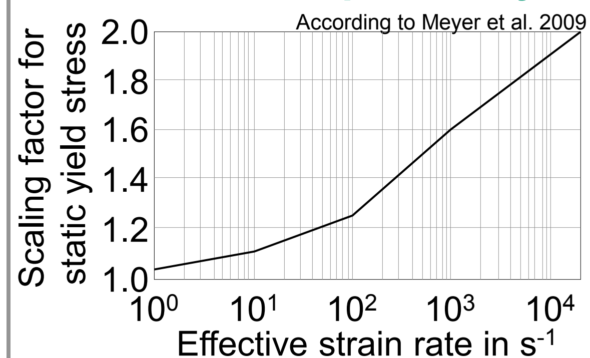
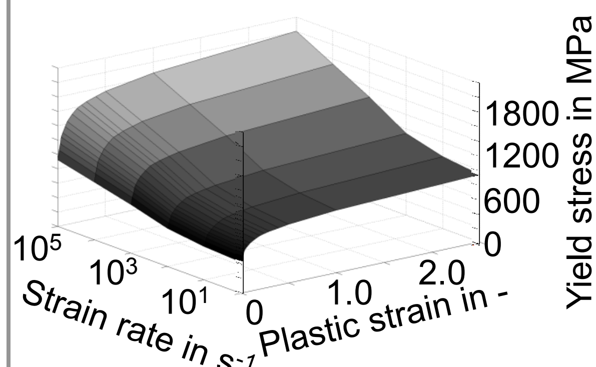


Strain rate dependency





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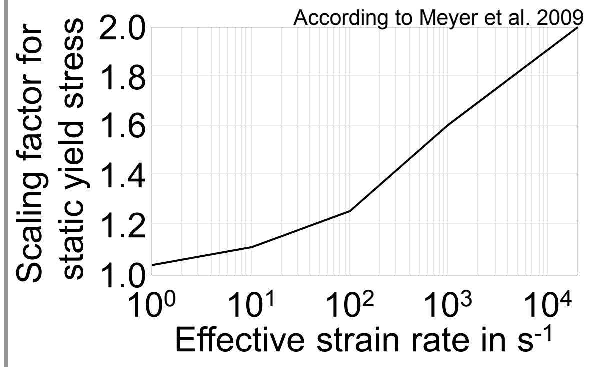
Material modeling

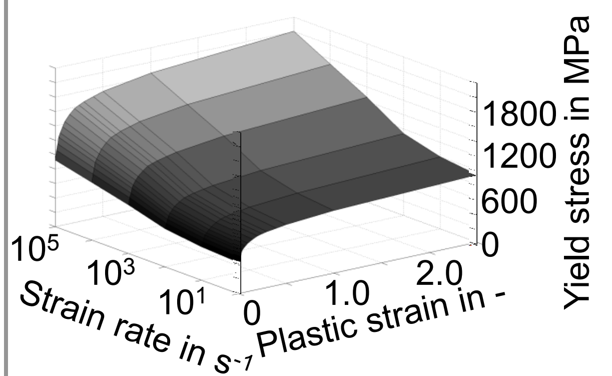
Magnetic field intensity

No significant influence of nonlinear magnetization detected

➔ Influence disregarded in the numerical analysis of the joining process

Strain rate dependency





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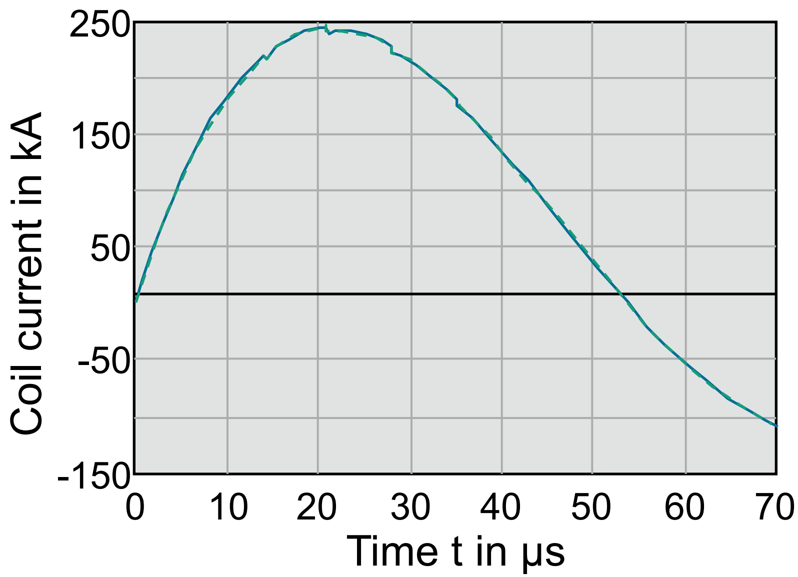
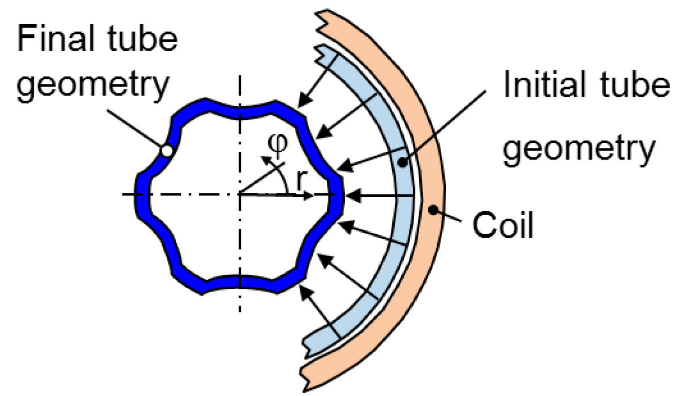
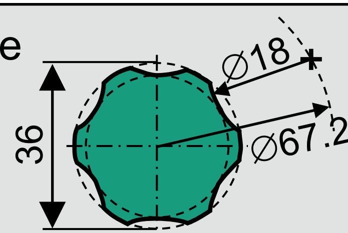
Results of the numerical analyses – Joining by EMF



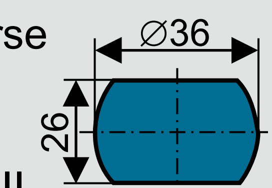


Calculated course of current and inductance for shaft geometry I



Charging voltage: 16 kV

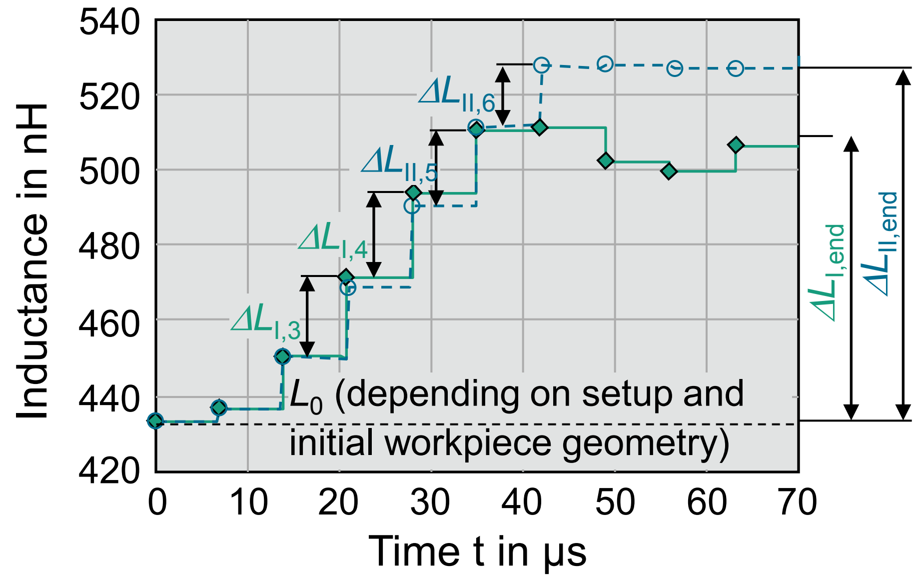
Calculated course of current and inductance for shaft geometry II



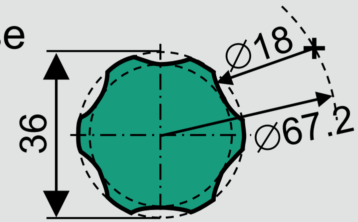
Charging voltage: 16 kV

Results of the numerical analyses – Joining by EMF

$$L(t) = L_0 + \Delta L(t) = L_0 + f\left(\Delta A\right)$$
$$= L_0 + f\left(\int \oint \left(r(\varphi,t) \frac{dr}{dt}(\varphi,t) \right) d\varphi \, dt \right)$$

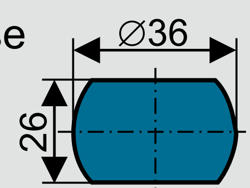


Calculated course of current and inductance for shaft geometry I



Charging voltage: 16 kV

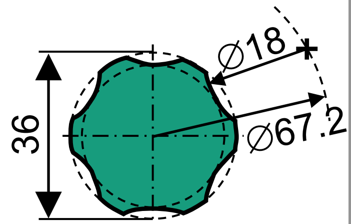
Calculated course of current and inductance for shaft geometry II



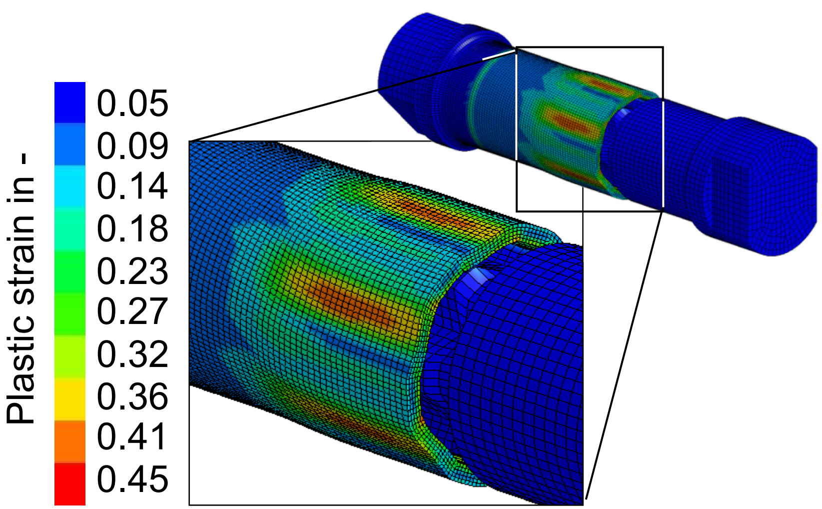
Charging voltage: 16 kV

Results of the numerical analyses – Testing of the joint

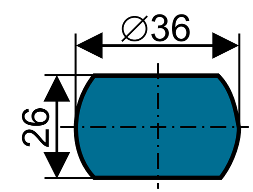
Shaft geometry I



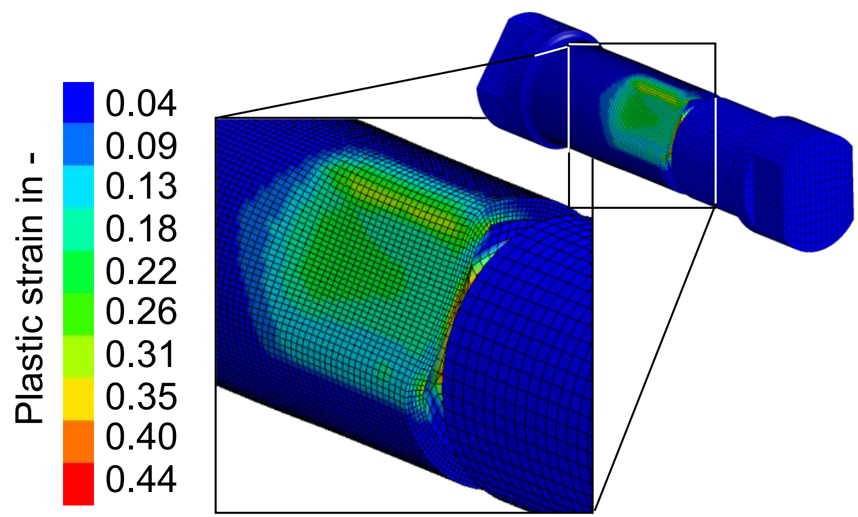
Max. displacement	2.7 mm
Rise of gap volume	97%
Max. local strain	0.45
Strain energy	1.0 kJ
Maximum torque	2300 Nm



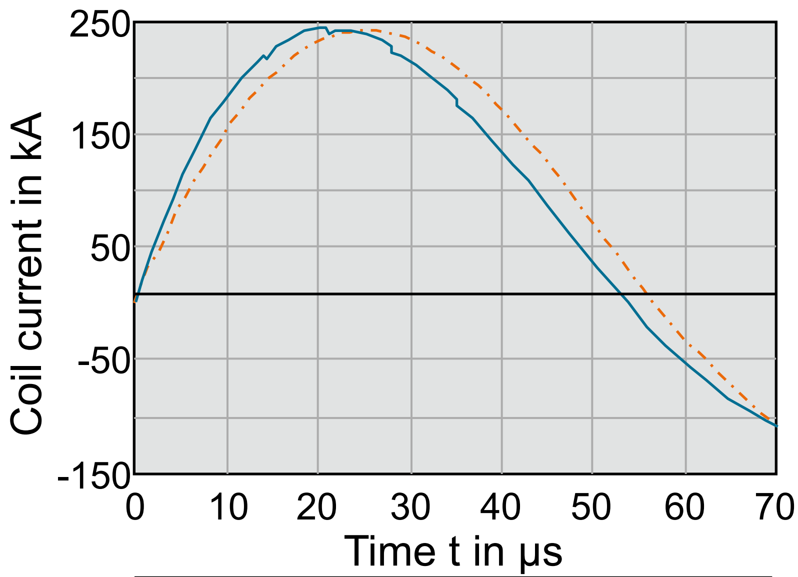
Shaft geometry II



Max. displacement	5.3 mm
Rise of gap volume	136%
Max. local strain	0.44
Strain energy	0.9 kJ
Maximum torque	1500 Nm



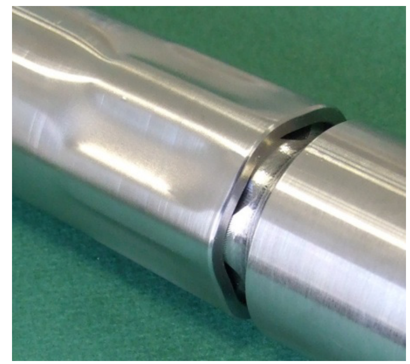
Experimental verification – Joining by EMF

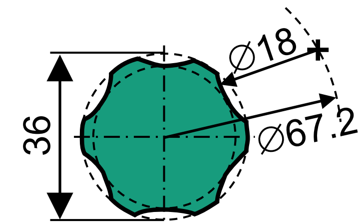


Calculated current

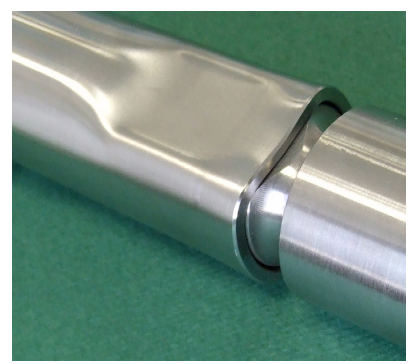
Measured current (mean value from 10 experiments)

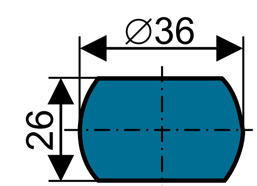
Shaft geometry I





Shaft geometry II





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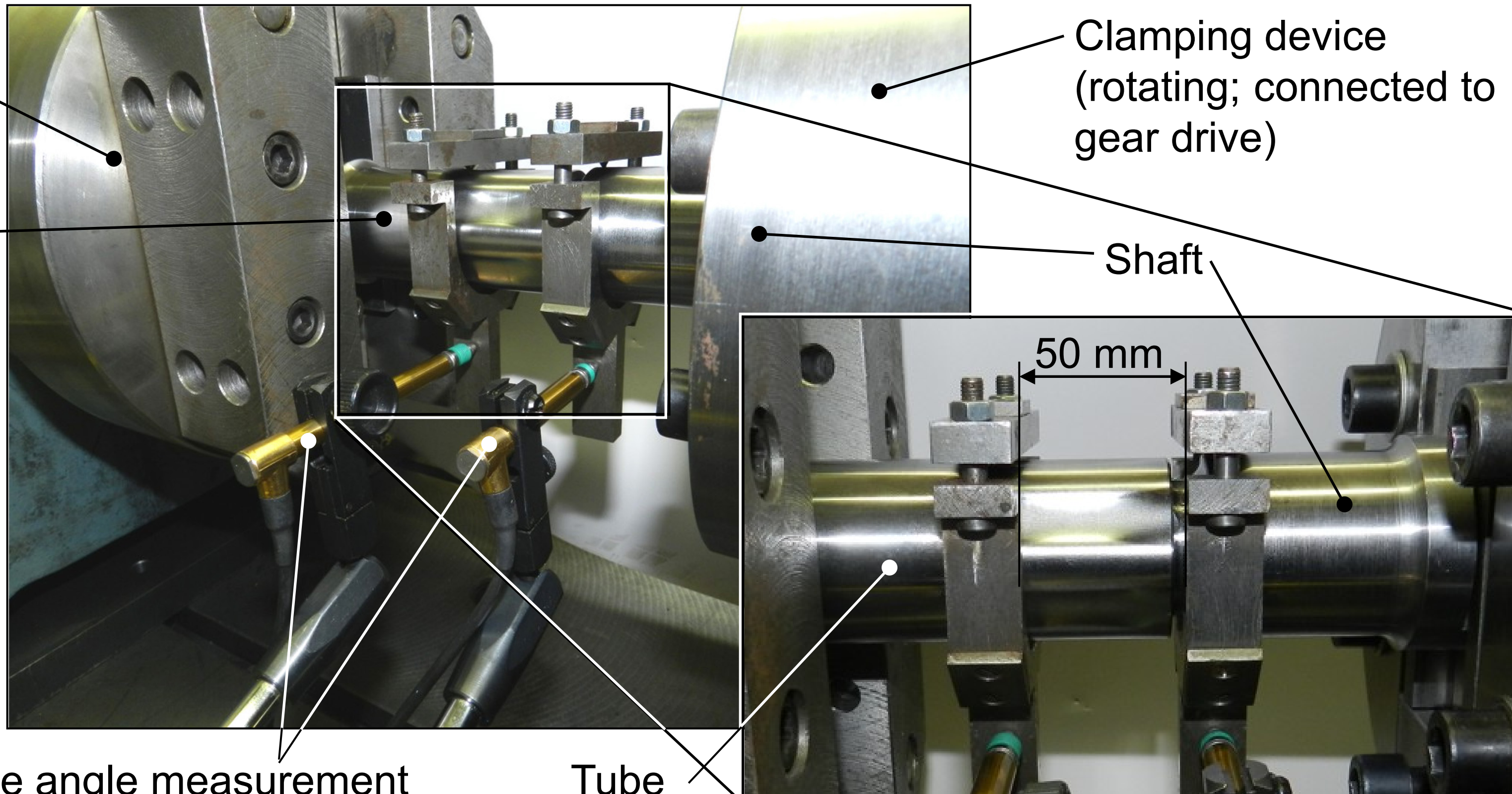
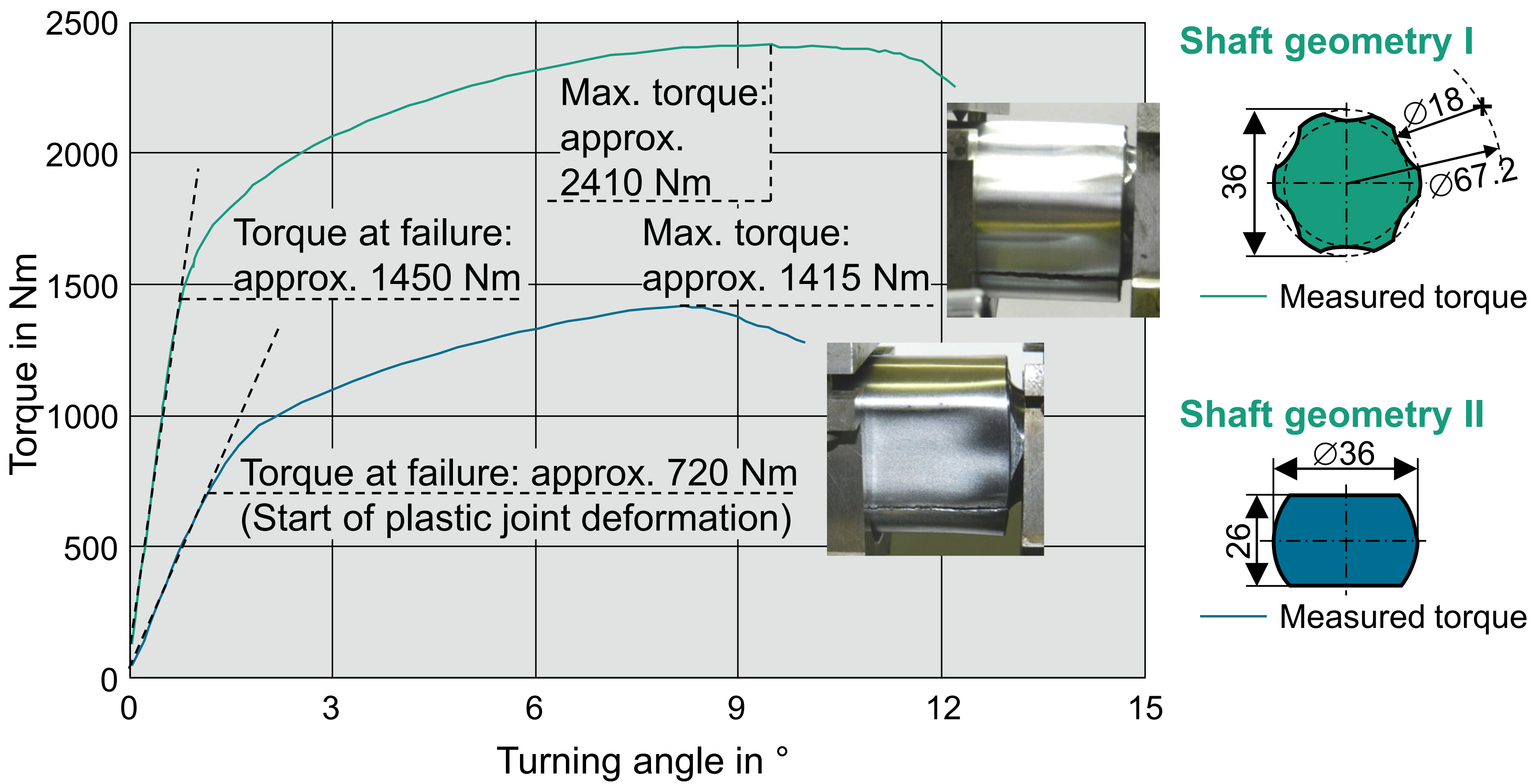
Experimental verification – Testing of the joint



Torque measurement device at Chemnitz University of Technology, Institute of Engineering Design and Drive Technology

Experimental verification – Joint strength



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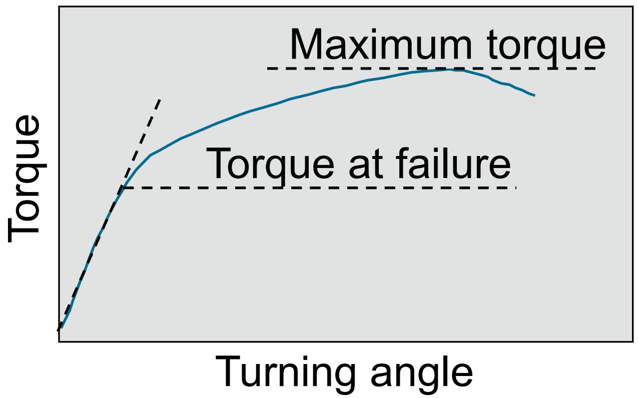
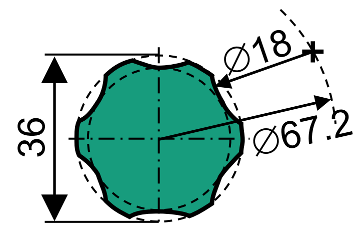
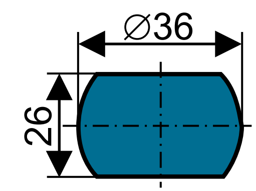
	Shaft geometry I 		Shaft geometry II 	
	Simulation	Experiment	Simulation	Experiment
Torque at failure in Nm	1350	1450	720	720
Maximum torque in Nm	2350	2410	1500	1415

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Summary

- A form-fit joint was designed on the basis of numerical investigations.
  - Simulation of the electromagnetic joining process and
  - Subsequent simulation of the torque loading
- Nonlinear magnetization of ferromagnetic materials has only minor influence in EMF-technologies.
- Strain rate dependency was considered via a scaling the static yield stress.
- The overall strain energy stored in the workpiece after joining is decisive with regard to the transferable torque.
- Knowing the max. displacement and strain is not sufficient for joint design.
- Experimental verification showed good qualitative and quantitative agreement with the simulation considering the achievable torque. (Failure type could not be predicted via this modeling.)