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TECHNISCHE UNIVERSITÄT CHEMNITZ

Kunststofftechnik Chemnitz

Optimisation of the joining strategy and residual stress considerations for heated tool welding of polyethylene with high wall thicknesses

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INDUSTRIELLE GEMEINSCHAFTSFORSCHUNG IGF

DVS FORSCHUNG

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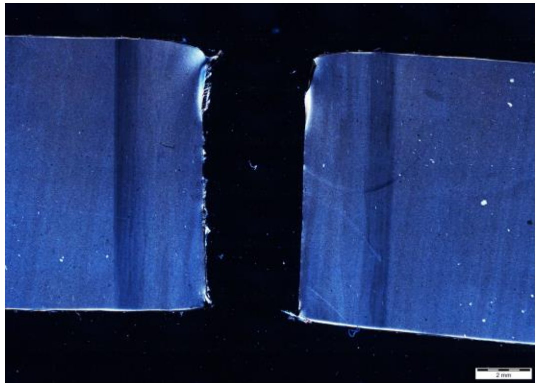
Outline



Introduction

Products

- Continuous replacement of steel pipes with more sustainable plastic pipes
- New containers and pipelines e.g. for
  - drinking water production and storage
  - expansion of sustainable infrastucture for renewable energies

Source: www.frank-gmbh.de

- ➢ Increasing diameters (3,500 mm) and wall thicknesses (200 mm)
- ➢ Expected service life up to 100 years
- ➢ Costly and time-consuming repairs in the event of damage

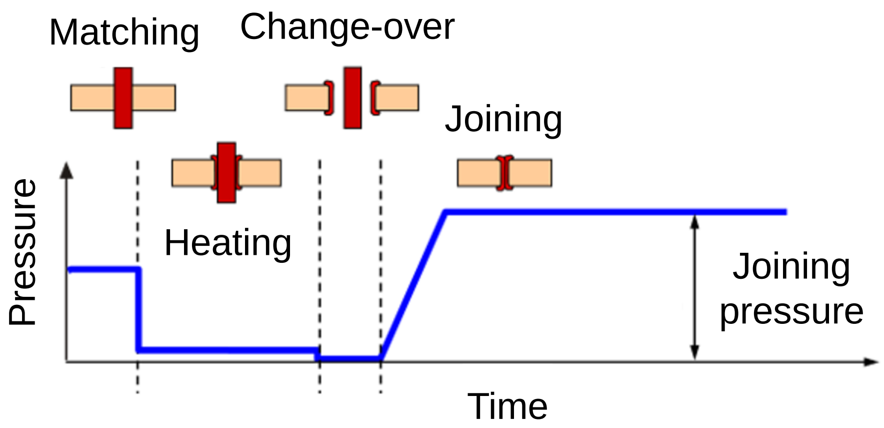
Material

Generations of PE-HD	
Material	Requirements
PE80	8 MPa 50 years
PE100	10 MPa 50 years
PE100 RC*	10 MPa 50 years

*Resistant to Crack

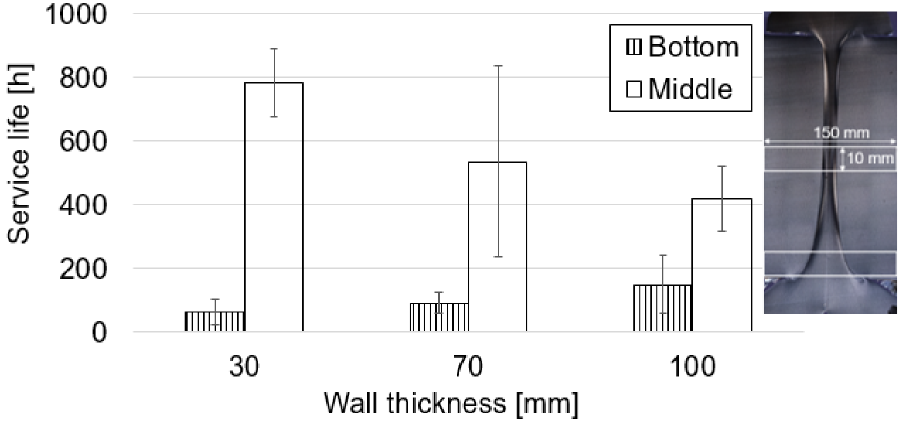
- Continuous development of polyethylene to improve long-term durability
- PE100 RC as the latest generation available for around 20 years

Welding procedure



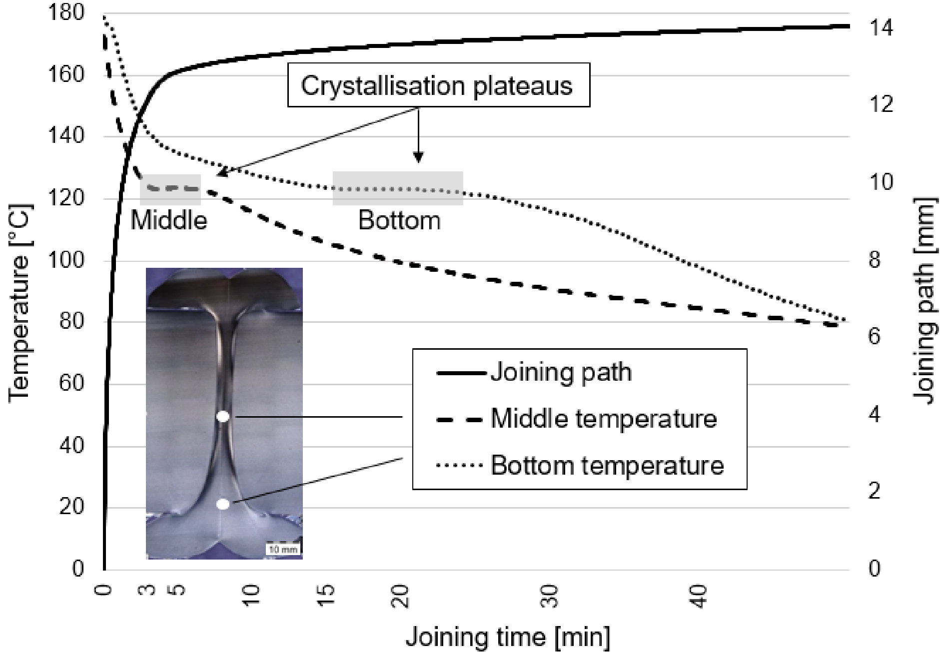
- Hot plate welding as the most common joining process in the area of semi-finished products
- Scientific studies only for wall thicknesses up to approx. 20 mm
- Linear extrapolated parameters for high wall thicknesses according to DVS 2207-1
- ➢ Necessity of a reliable process control for heated tool welding of polyethylene with high wall thicknesses

State of the art / Previous research findings



Long-term tensile creep test of PE100 RC,
wall thickness 30 – 100 mm
(welding parameters according to DVS 2207-1)

- Short service life in the curved, lower edge area of the weld seams for all wall thicknesses
- No improvement through variation of single parameters



Cooling curves and joining path of PE100 RC, wall thickness 100 mm

- Different crystallisation times between the middle and the bottom due to thermal restructuring of the melt during the joining phase
- Further continuous increase in joining path from the start of crystallisation above thermally induced contraction

➢ Mechanical load on the solidifying weld seam due to continuous joining pressure

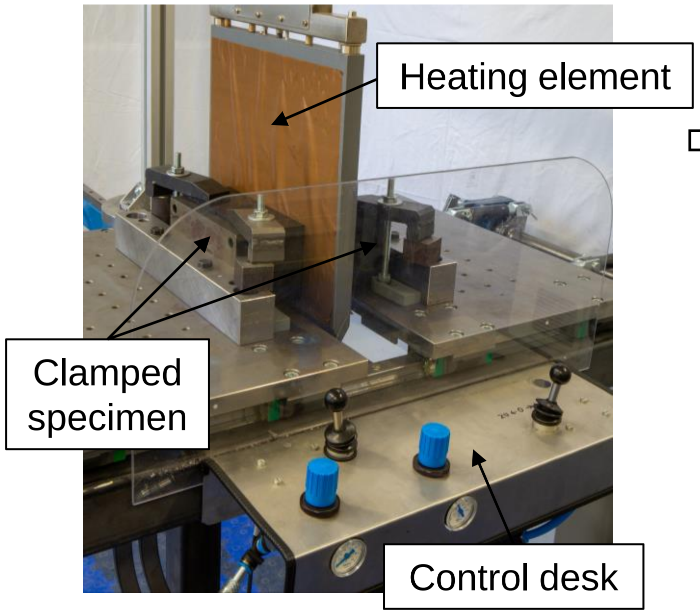
➢ Further investigations required to reduce the long-term strength gradient with a modified process strategy

Experimental

Material / specimen

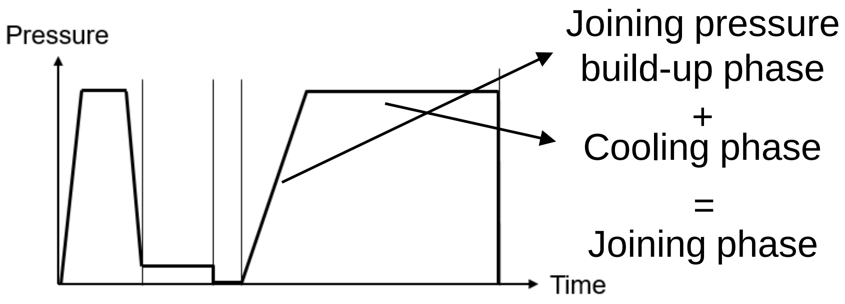
Material	Specimen	Wall thickness
PE100 RC	Panels (pressed, black colour)	30 mm 100 mm

Pneumatic welding machine



- Max. joining force: 20,000 N

Welding tests



- Process investigation and optimisation of the joining phase
  - ➢ Correlation of the joining time with the cooling temperature

Joining strategy no.	Joining pressure	Joining time
1 (DVS)	0.15 MPa	120 min
2	0.15 MPa	1 min
3	0.45 MPa	1 min 45 s

(Successful initial tests with p_j > 0,45 MPa not pursued further due to limited industrial feasibility)

- Process control by means of temperature and joining path measurement

Material testing

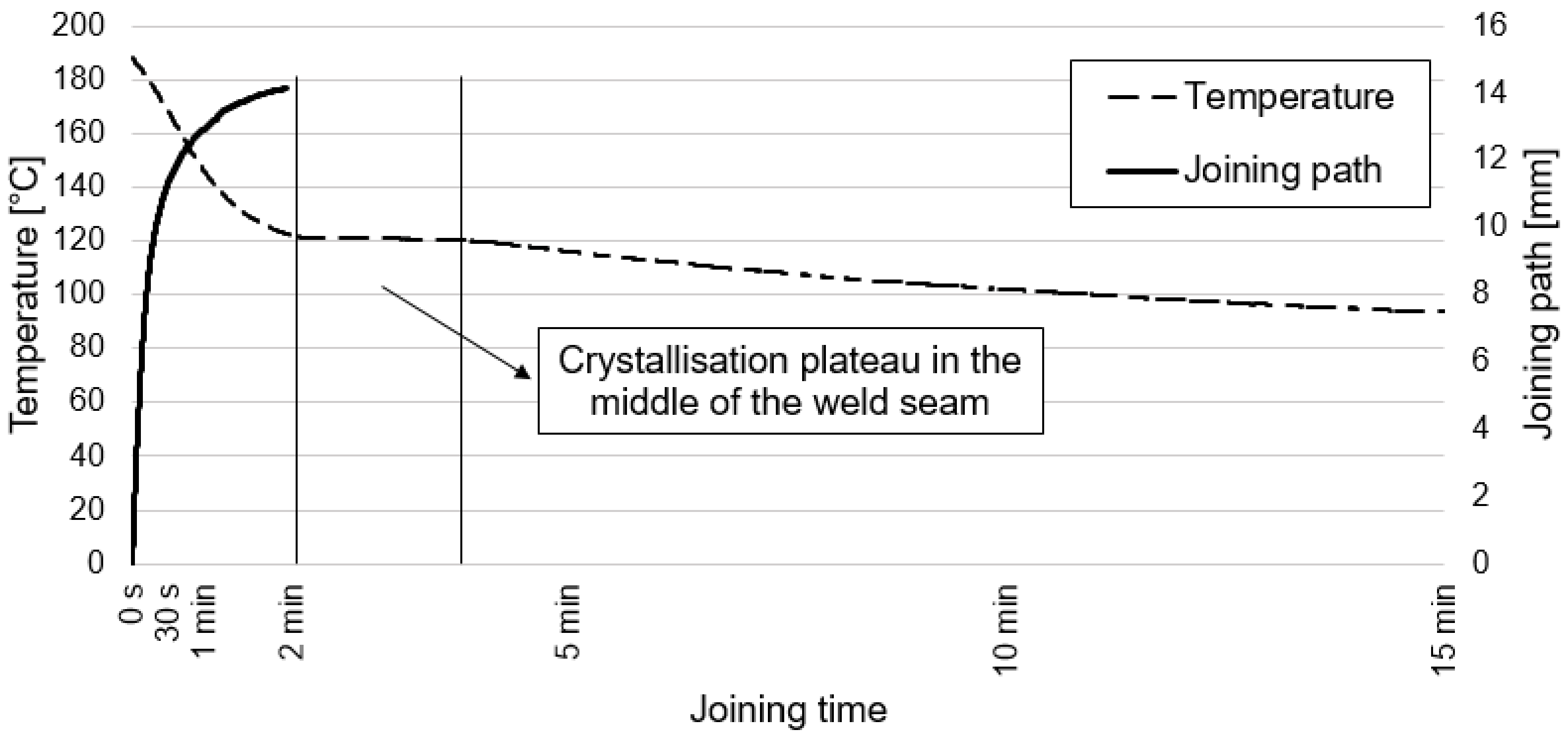
- Mechanical analysis
  - – Tensile creep test (DVS 2203-4)
    → long-term behaviour
    - ○ Local sampling from the middle and the bottom of the weld seam
    - ○ Test load: 4 MPa
    - ○ Test temperature: 90 °C
  - – Tensile test, bending test, impact bending test
- Additional microscopic / visual / rheological examinations
- Residual stress analysis

Process

Structure ⟷ Properties

Results and Discussion

Variation of the joining phase procedure, wall thickness 100 mm

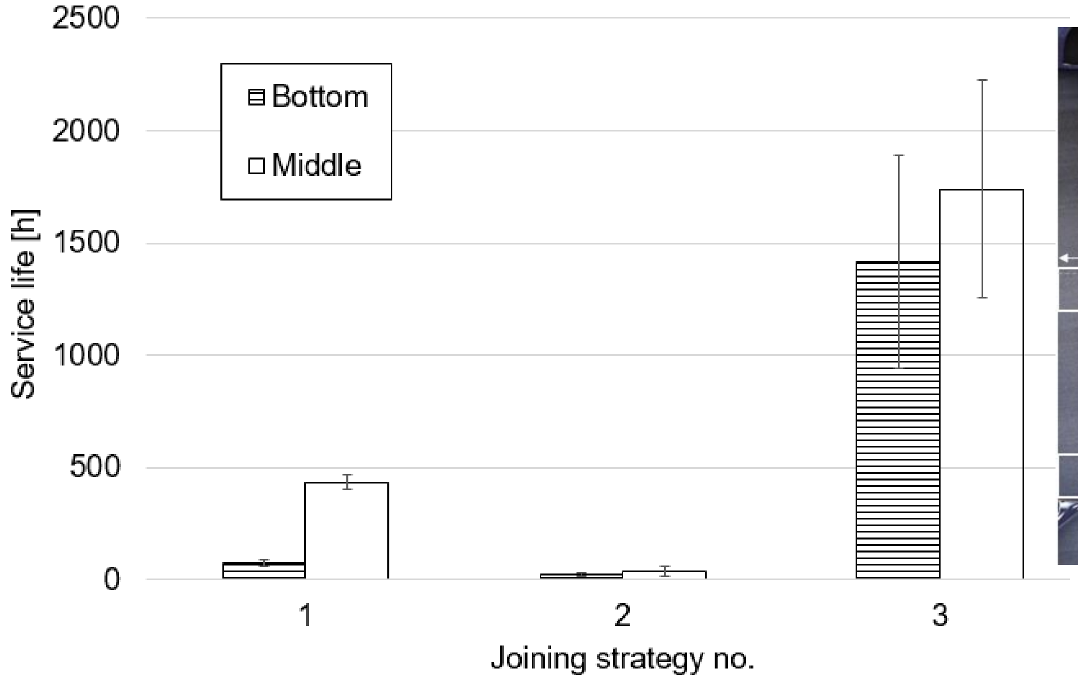


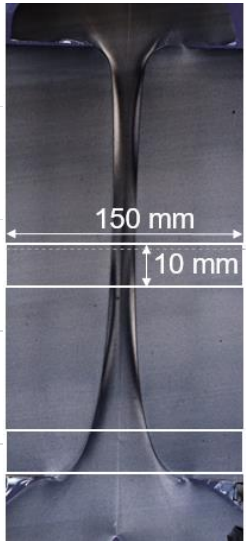
Joining path and cooling temperature with joining strategy no. 3 (joining pressure 0.45 MPa, joining time 1 min 45s), wall thickness 100 mm

- End of the joining pressure before reaching the crystallisation → pressureless solidification of the weld seam
- Joining path of approx. 14 mm corresponds to the joining path measured with joining strategy no. 1 (DVS)

Results and Discussion

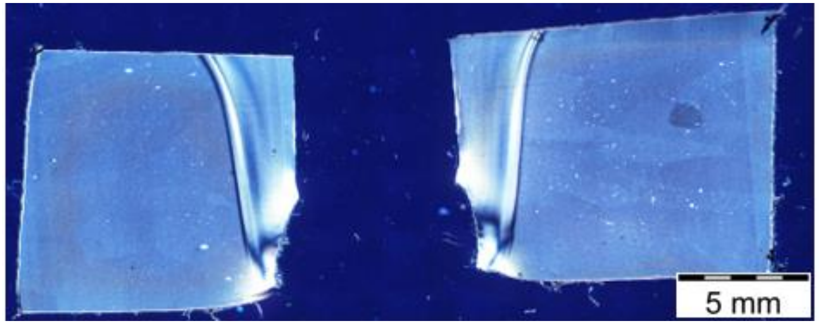
Service life of the various joining strategies in the tensile creep test, wall thickness 100 mm





Joining path	14 mm	9.5 mm	14 mm

Joining strategy no.	Joining pressure	Joining time
1 (DVS)	0.15 MPa	120 min
2	0.15 MPa	1 min
3	0.45 MPa	1 min 45 s

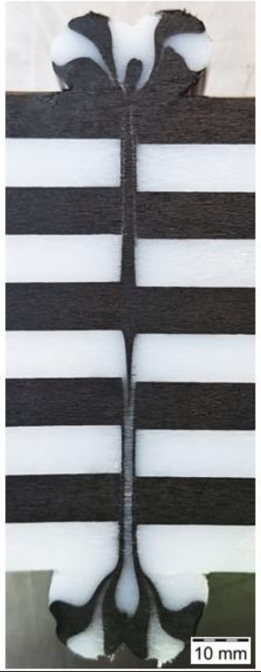


Microscopic fracture surface analysis
(exemplary for joining stragety no. 3)

- Fracture progression through the joining plane (brittle crack initiation in the edge area with ductile residual fracture surface)
- ➢ No different fracture patterns observed with different joining strategies
- ➢ No differences in polarisation microscopic observations of the joining planes

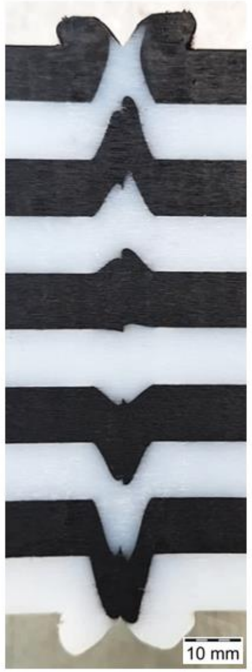
Visualisation of the melt flow through the welding of multi-coloured plates

*Reduced measured joining paths due to skipped matching phase



Joining strategy no. 1
p_j = 0.15 MPa
t_j = 120 min
→ Joining path 12 mm*

Joining strategy no. 3
p_j = 0.45 MPa
t_j = 1 min 45 s
→ Joining path 12 mm*



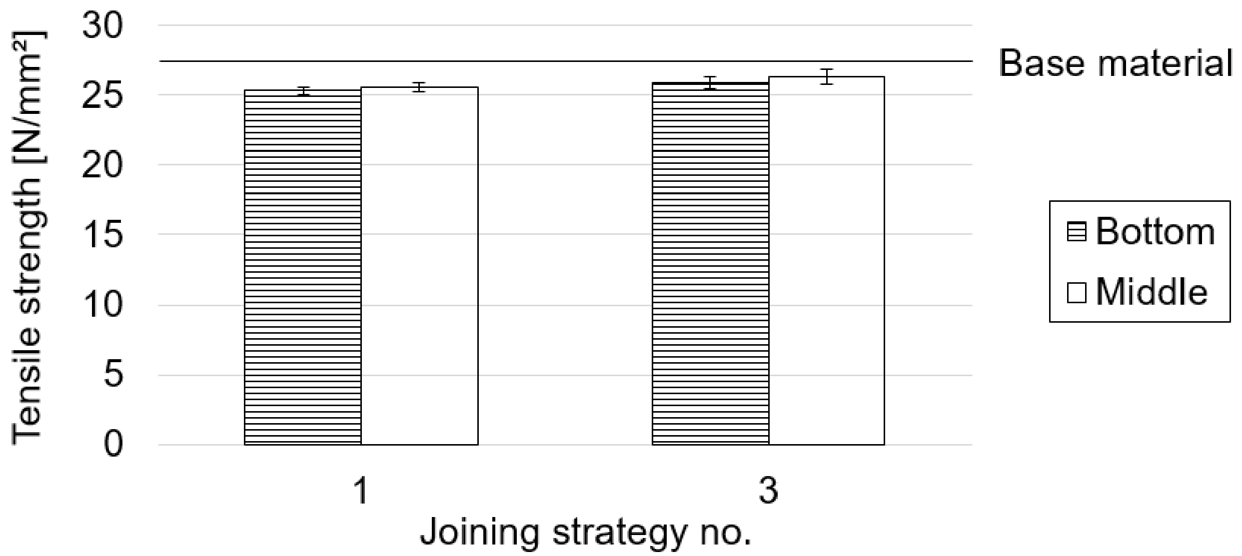
Dual-Low-Pressure (ISO 21307)
p_j = 0.15 MPa
t_j = 10 s
→ Joining path 4 mm

- Clear correlation between the measured joining path and the flow paths of the melt in the joining plane
- Almost no interlocking of the individual plates with Dual-Low-Pressure process

➢ Necessity of a sufficient joining path to create the melt flow required for long-term strength

Results and Discussion

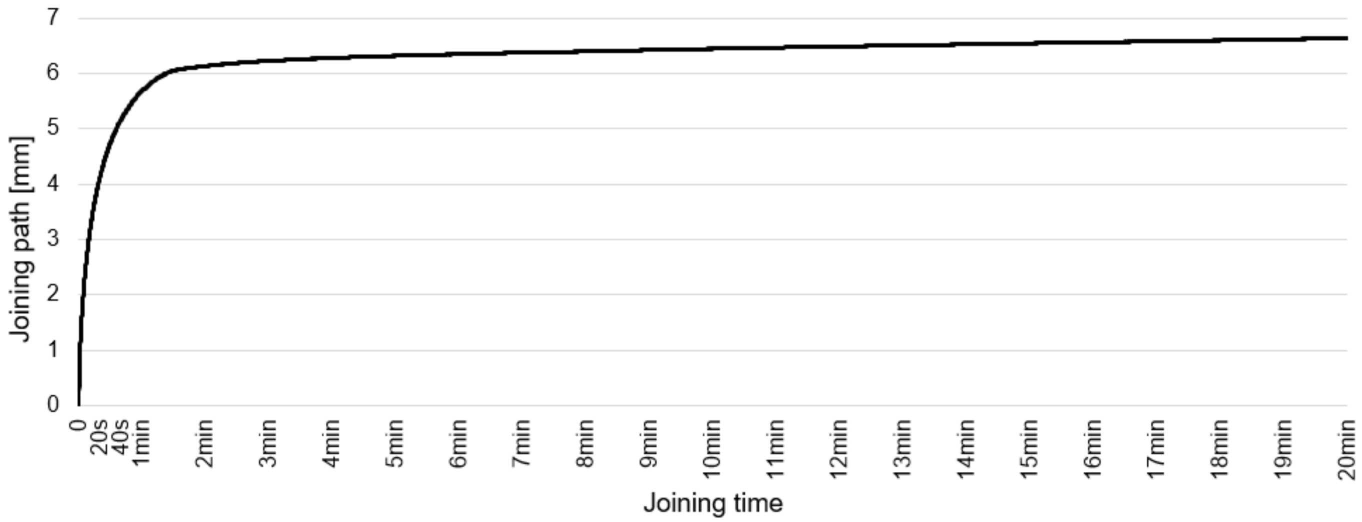
Short-term mechanical behaviour of different joining strategies, wall thickness 100 mm



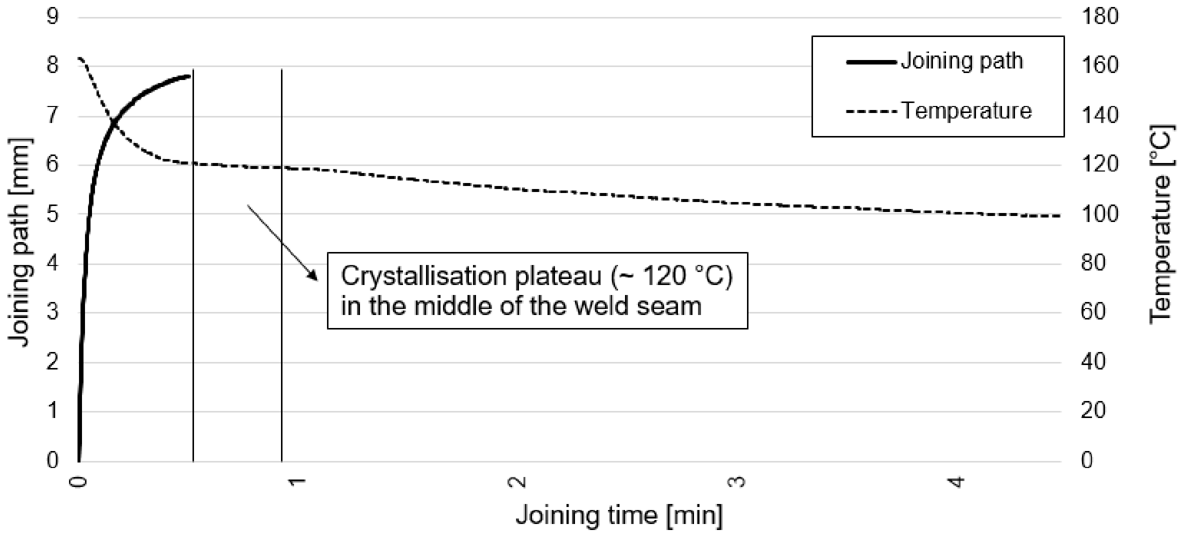
Tensile strength of the base material and the weld seams (testing procedure according to DVS 2203-2)

- No significant differences between the joining strategies and the tested positions in the weld seam
- Achievement of the required short-term welding factor of 0.9 according to DVS 2203-1
- No failure of the specimens in the bending and impact bending test

Transfer of the joining strategy to a wall thickness of 30 mm



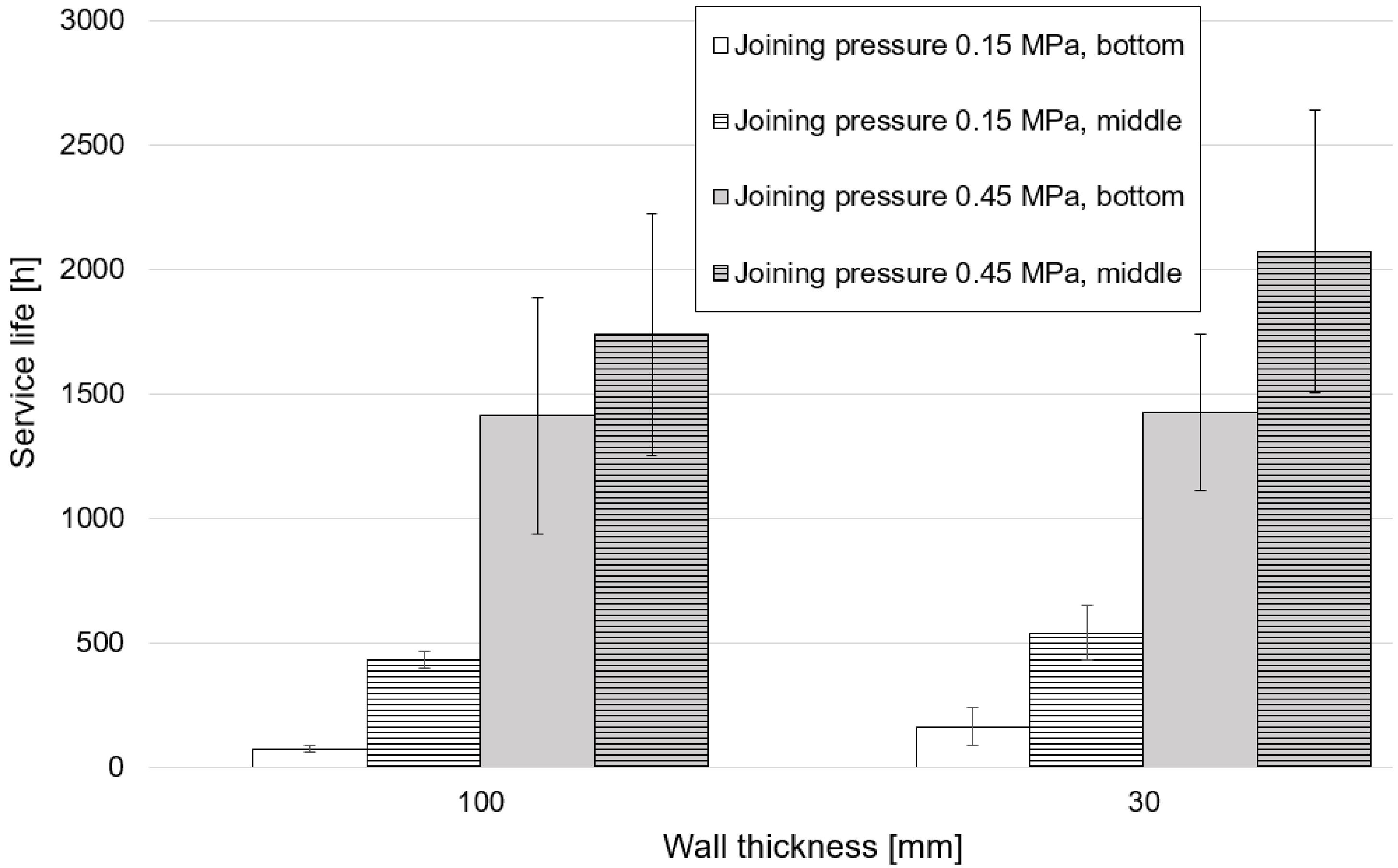
Joining path according to DVS 2207-1 (joining pressure 0.15 MPa, joining time under pressure 40 min), wall thickness 30 mm



Cooling temperature and joining path according to modified joining strategy (joining pressure 0.45 MPa, joining time under pressure 30 s)

Transfer of the joining path measured according to DVS to modified joining strategy

Service life of different joining strategies in the tensile creep test, wall thickness 30 mm



Wall thickness	Joining pressure	Joining time	Joining path
100 mm	0.15 MPa	120 min	14 mm
100 mm	0.45 MPa	1 min 45 s	14 mm
30 mm	0.15 MPa	40 min	7 mm
30 mm	0.45 MPa	30 s	7.8 mm

- Similar improvement in long-term mechanical properties with different wall thicknesses
  - ➢ Successful transfer of the joining strategy to a wall thickness of 30 mm

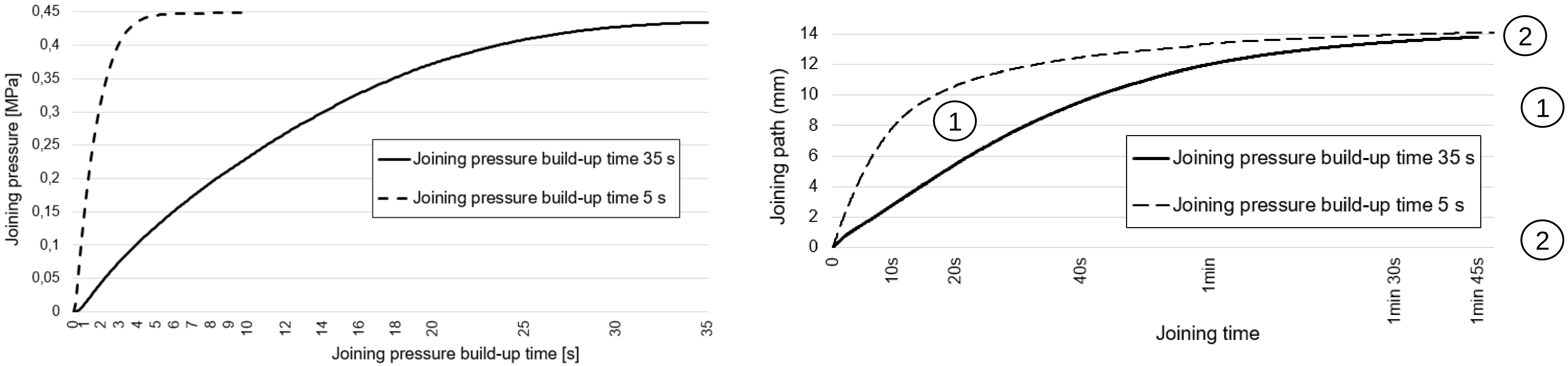
Results and Discussion

Variation of the joining pressure build-up phase, wall thickness 100 mm

- Significant part of the joining path and therefore the melt flow already taking place during the joining pressure build-up phase

➢ Influence of the joining pressure build-up phase / further optimisation potential with regard to the achievable long-term strength?

Maximum achievable joining pressure build-up speed of the welding system → ~ 5 s	← Implementation of the joining pressure build-up variation by throttling the volume flow of the pneumatically driven welding system →	Maximum permissible joining pressure build-up time according to DVS 2207-1 → 35 s



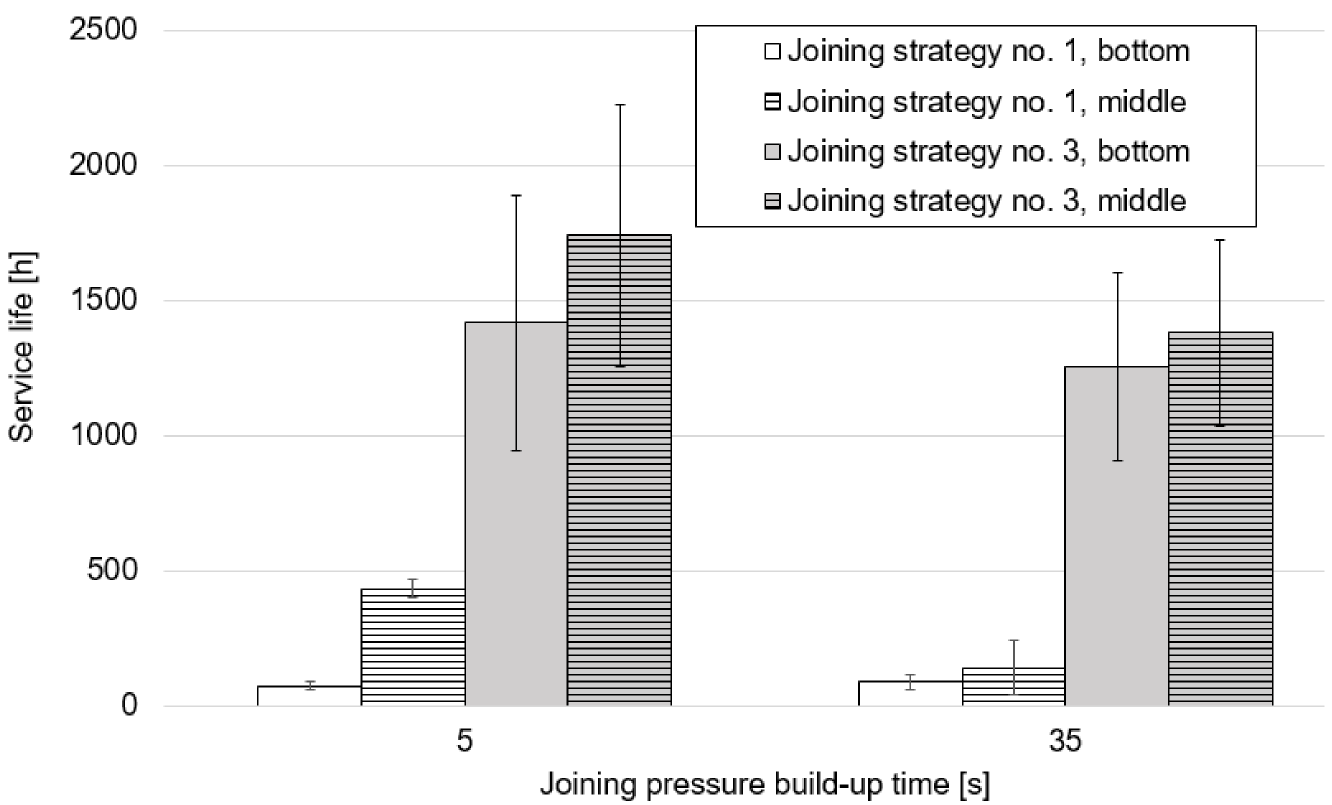
Course of the joining pressure (left) and joining path (right) up to a joining pressure of 0.45 MPa (joining strategy no. 3)

1. Different timing of the melt flow
2. No difference in the overall joining path

- Analogue determination of the joining pressure and the joining path for joining strategy no. 1 (p_j = 0.15 MPa)

Results and Discussion

Influence of the joining pressure build-up phase variation on the long-term mechanical properties, wall thickness 100 mm



- ➢ Minor influence of the joining pressure build-up time and thus the melt flow rate on the long-term strength
- ➢ Influence of the joining pressure build-up time significantly lower than influence of the joining strategy

- ➢ Further tests with a joining pressure build-up time of 20 s currently ongoing

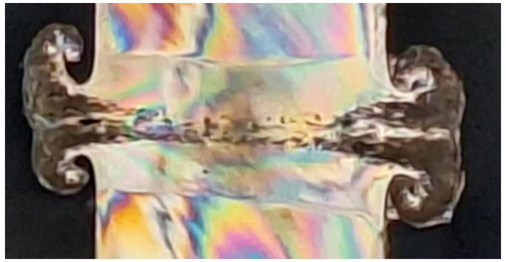
Results and Discussion

Residual stress considerations

- 3 different approaches for the indirect determination of the residuall stress condition in the weld seam

1. Optical investigation of amorphous weld seams made of polycarbonate
- Investigation of photoelasticity in the polariscope
  - ➢ No local differences in the weld seam visible
- Investigation of environmental stress cracking using the bending strip method (test liquid: ethyl acetate / methanol 1:3)
  - ➢ No localised stress cracking visible before failure of the entire weld seam

(No completely stressless condition of the base material achieved despite long-term tempering)

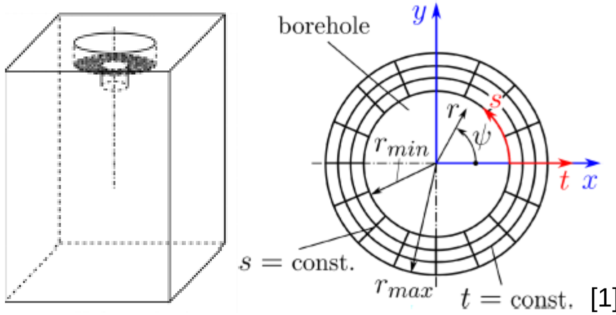


Polariscopic examination of the polycarbonate weld seam

Environmental stress cracking test

2. Borehole drilling method
- Investigations in cooperation with the Professorship of Solid Mechanics
- Procedure:
  - ➢ Deformation analysis of the surrounding area of a borehole with strain gauges
  - ➢ Correlation of the deformation with the residual stress state

➢ Trials currently ongoing



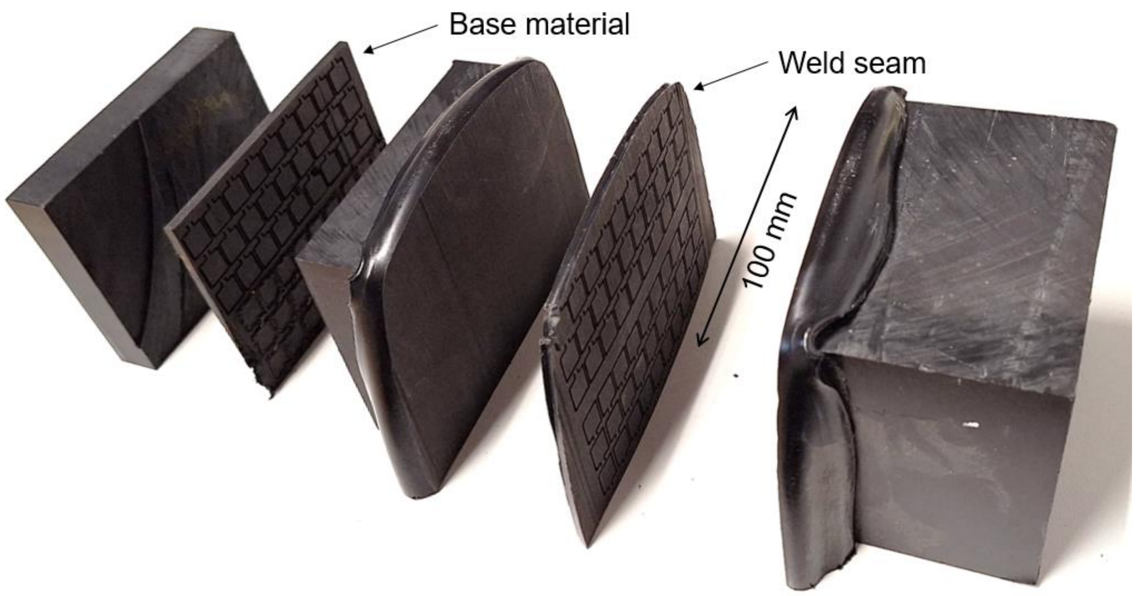
Schematic illustration of the borehole drilling method [1]

[1] Lehmann et.al: Strain, 61 (2025), https://doi.org/10.1111/str.70002

Residual stress considerations

3. Measurement of dimensional change using thermomechanical analysis (TMA)

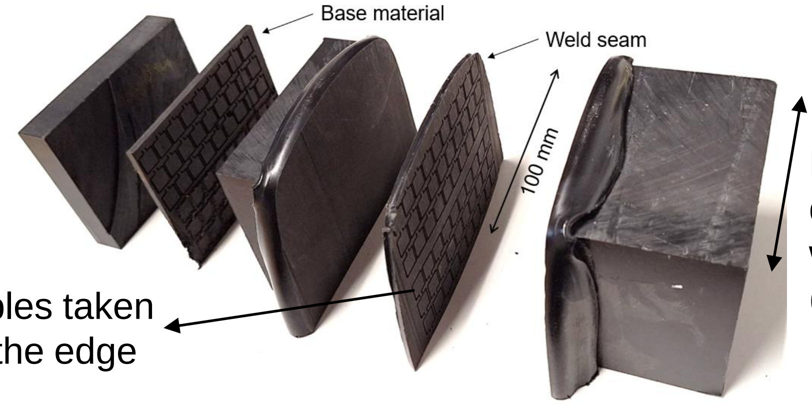
- Determination of the dimensional change caused by heat treatment of the sample
- Temperature program: Two heating and cooling cycles (0 °C → 100 °C; 3 K/min)
- ➢ Correlation of the dimensional change with the residual stress state



Local sample preparation from the weld seam and the base material using water jet cutting

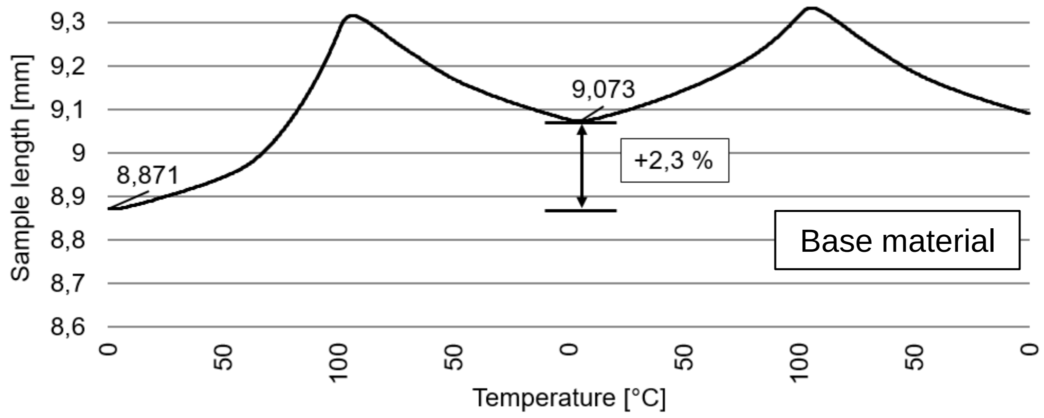
Results and Discussion

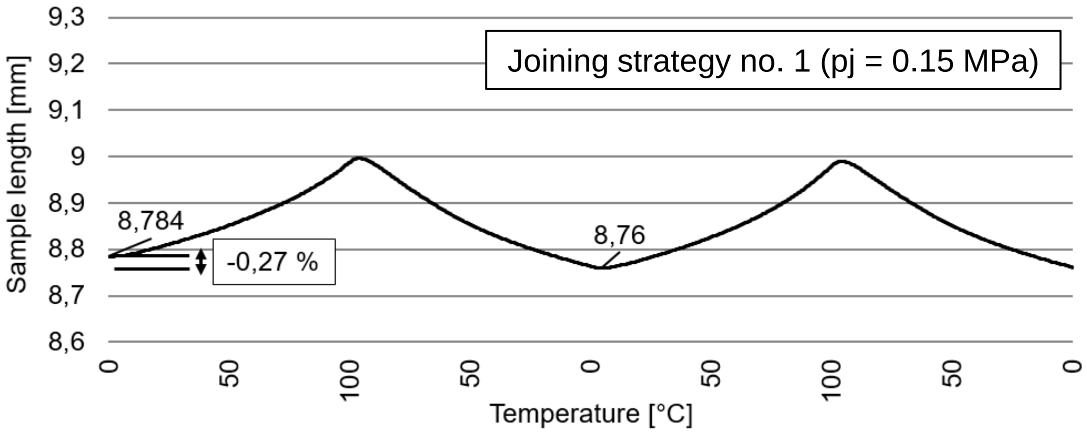
Residual stress considerations

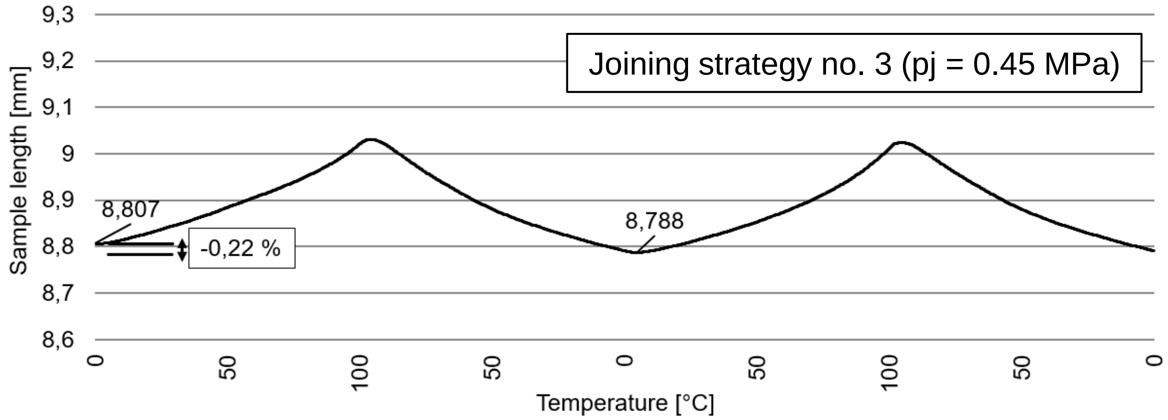


Measurement of the dimensional change in the wall thickness direction (flow direction of the melt)

Samples taken from the edge







- Clear difference between base material and weld seam
- Slight difference between the individual weld seams

➢ Further trials currently ongoing

Summary and Outlook

Summary

- Improvement of long-term mechanical properties by optimising the joining strategy
  - ➢ Adjustment of the joining time to the cooling dynamics in the weld seam
  - ➢ Successful application of the modified joining strategy for wall thicknesses of 30 and 100 mm
- Minor influence of the joining pressure build-up time on the weld seam strength

Outlook

- Expanding the understanding of the morphology in the weld seam and thus the failure behaviour of different joining strategies (e.g. by scanning electron microscopy of etched samples and by density measurements)
- Transfer of the joining strategy to the hot plate welding of pipes and plates on an industrial scale
- Determination of suitable and industrially applicable parameter sets for different wall thicknesses
  - ➢ Implementation of the process strategy in the DVS guideline
  - ➢ Industrial application of the developed process strategy for hot plate welding with high wall thicknesses

Thank you for your attention!

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