Programm NANU: “Funding of junior research groups in nuclear safety research at German universities“

funded by:

Federal Ministry
for the Environment, Nature Conservation,
Nuclear Safety and Consumer Protection

Critical assessment of the safety of innovative, future-proof manufacturing processes for internationally relevant SMR concepts

Kritische Bewertung der Sicherheit von innovativen, zukunftsfähigen Fertigungsverfahren für international relevante SMR-Konzepte

acronym: SiFeKo

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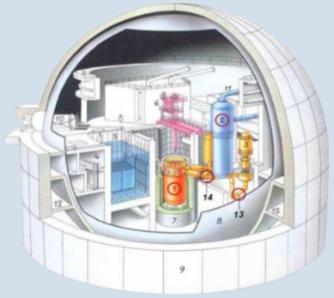
SiFeKo

Project Overview

Global Motivation: demand for more low-CO_2 / carbon-free forms of energy generation promotes the development of new reactor concepts, like small modular reactors (SMR).

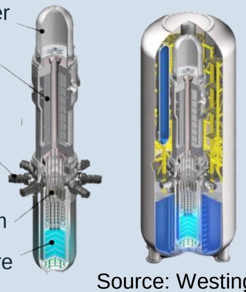
Current PWR



Construction:	3 … 15 years
Core diameter:	~ 4 m
Refueling:	1 year
Power:	1.400 MW(e)

1985 - today

SMR

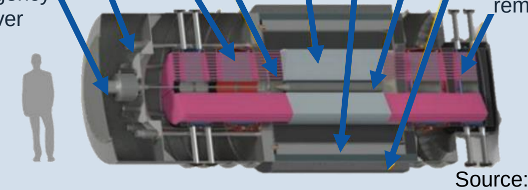


Source: Westinghouse

Construction:	1 year
Core diameter:	~ 2 m
Refueling:	2 years
Power:	250 MW(e)

2025

Solid State SMR „eVinci“



Source: Westinghouse

Construction:	30 days
Core diameter:	~ 0.5 - 1 m
Refueling:	7 years
Power:	5 MW(e)

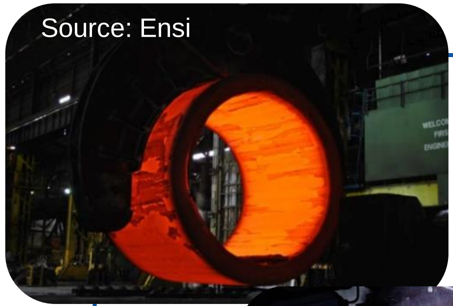
2030

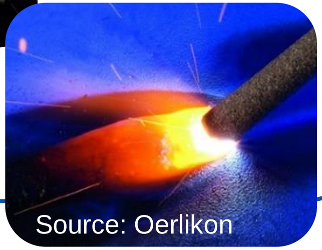
Our goals: - sustain competence in nuclear safety and develop safety relevant knowledge

- keep track of international trends and technologies regarding safety

-> development of new reactors and manufacturing technologies is not part of funding!

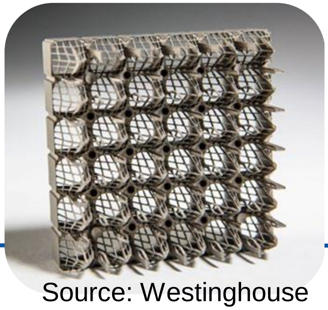
Traditional Manufacturing Processes





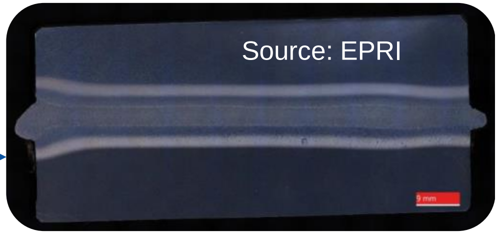
Advanced Manufacturing Processes

WAAM < 320 to & SLM < 35 kg

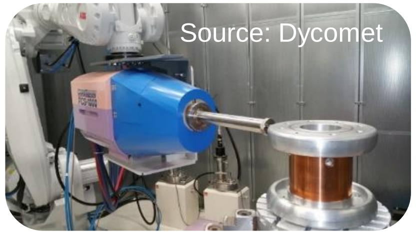


HIP < 4500 kg

Electron beam welding (< 200mm)

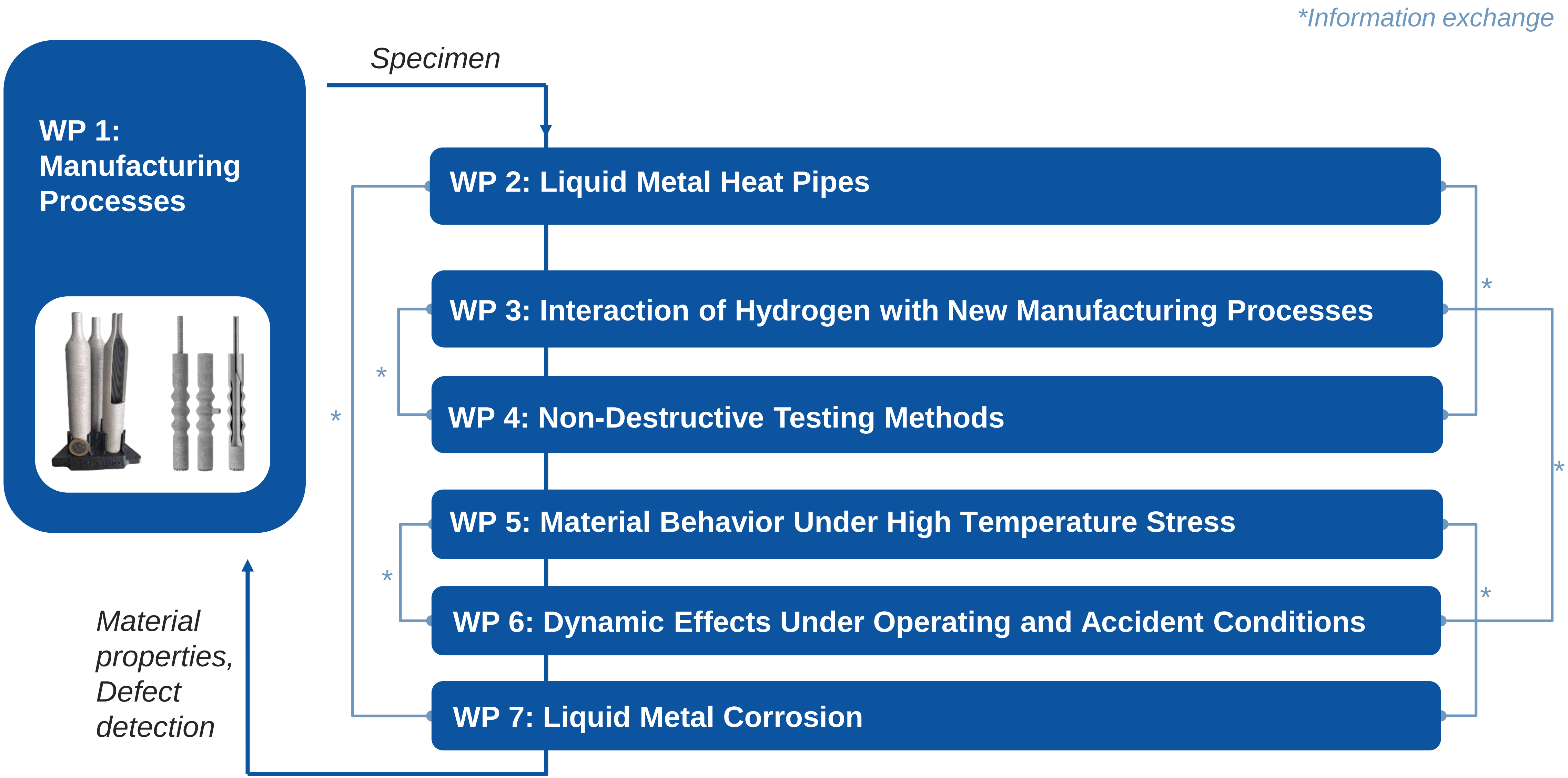


Cold gas spraying (< 25 mm)



SiFeKo

Project Overview



WP 1: Manufacturing Processes

WP1.1: Literature review on manufacturing parameters and expected process inaccuracies and failures and their impact on safety

WP1.2: Definition of test specimens and their manufacturing parameters for safety evaluation

WP1.3: Manufacturing of the specimens and a preparation for subsequent investigations

WP1.4: Basic mechanical characterization of the test specimens

WP1.5: Comparative assessment of the impact on safety

Examined manufacturing processes

- Laser Powder Bed Fusion (LPBF)
- Wire Arc Additive Manufaturing (WAAM)
- Hot Isostatic Pressing (HIP)
- Electron Beam Welding (EBW)
- Cold Gas Spraying (CS)

WP 1: Manufacturing Processes

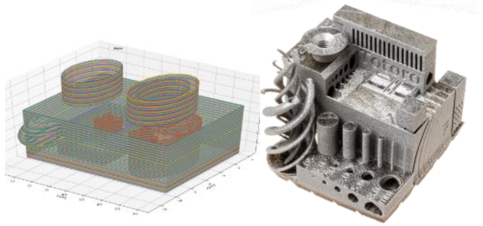
Contents of work

- Active tracking of international developments
- Determination of representative geometries and manufacturing strategies for the materials 316L, IN718 and 22NiMoCr3-7
- Acquisition and generation of test specimens from candidate materials
- Specimen analysis
- Estimation of process capability and robustness
    - LPBF
    - WAAM
    - EBW
    - HIP
    - CS

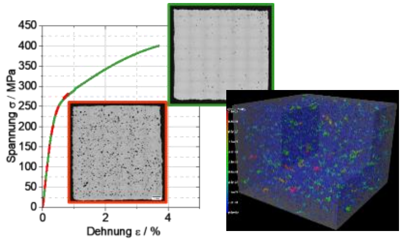
➡ Provision of representative material and test specimens for subsequent subprojects 2-7

Manufacturing process

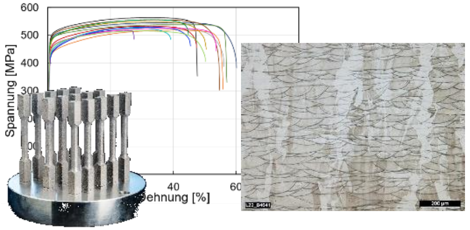
Manufacturing strategy



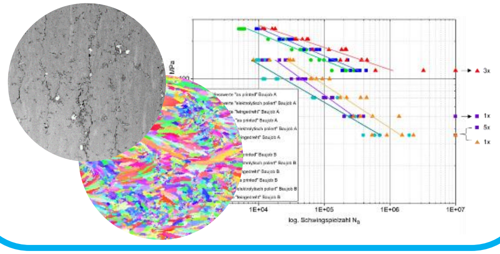
Manufacturing parameters



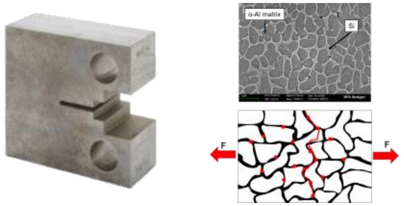
Basic characterization



Detailed characterization

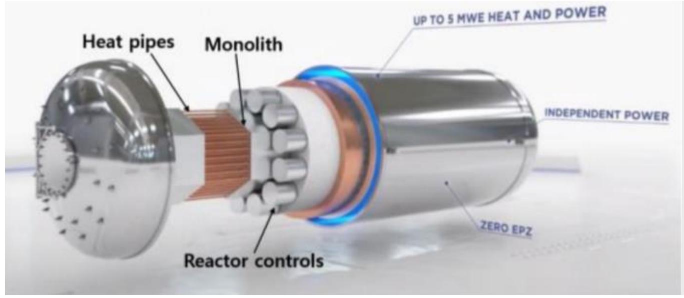


estimation of
structural safety



WP 2: Liquid-Metal Heat Pipes

Motivation:
- ➢ Passive heat transport using innovative liquid metal heat pipes (LM-HP) in vSMRs
- ➢ Heat pipes are an integral part of the safety and functional concept of vSMRs



Objective:
- Design and additive manufacturing of innovative LM-HP taking into account conceptual application requirements for vSMRs
- Determine functional aspects and limits
- Experimental investigation of the heat transfer characteristics of AM-manufactured LM-HP for relevant thermal vSMR operating conditions including postulated accident scenarios

WP 2.1: Selection of LM-HP Design Variants

Consideration of AM processes
Constructive design of prototype
LM-HP variants for WP 2 and WP 3

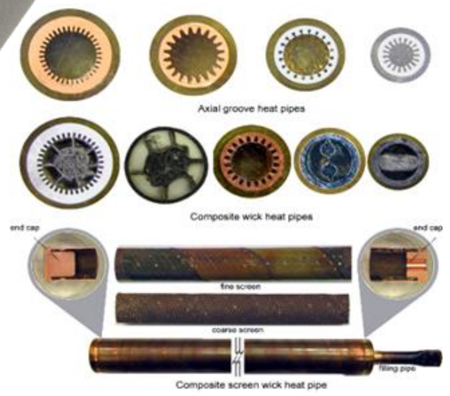
WP 2.2: AM Manufacturing

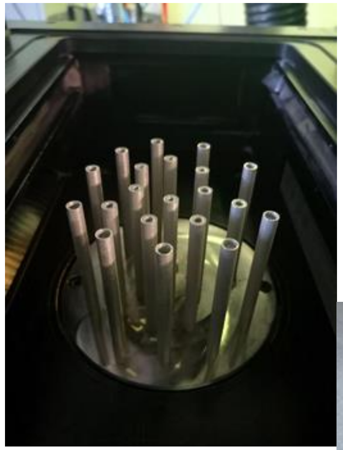
Production of test pieces and prototype LM-HP variants
Construction of a test bench
Provision of LM-HP filled with heat transfer fluid potassium

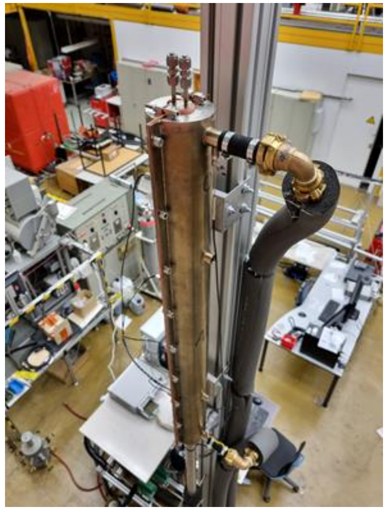
WP 2.3: Experimental Test Program

Qualification on AM-manufactured samples
Variation of thermal boundary conditions (550 - 750 °C) Start-up behavior, unsteady/stationary heat transport

WP 2: Liquid-Metal Heat Pipes





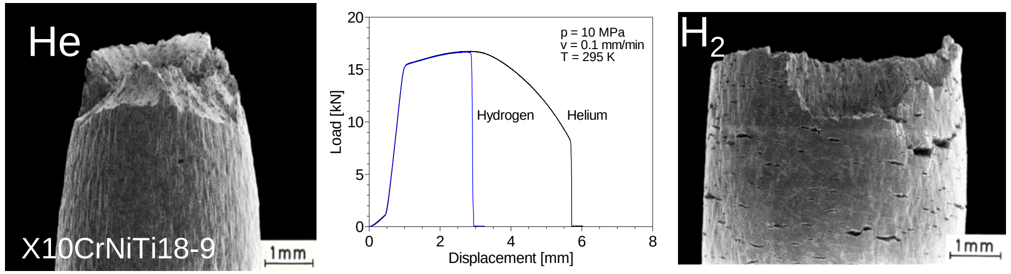


Design → Manufacturing → Testing

WP3: Interaction of Hydrogen with New Manufacturing Processes

Materials can become brittle under the direct influence of hydrogen

- Hydrogen embrittlement can lead to a reduction in ductility, fracture toughness and fatigue life.
- What is the influence of hydrogen on additively manufactured parts?



Objective of this work package

Gain insight into the hydrogen suitability of different additively manufactured materials

WP 3.1: Literature review

Collection of data referring to the mechanical-technological behavior under hydrogen atmosphere
Basis for modelling the service life under the influence of hydrogen

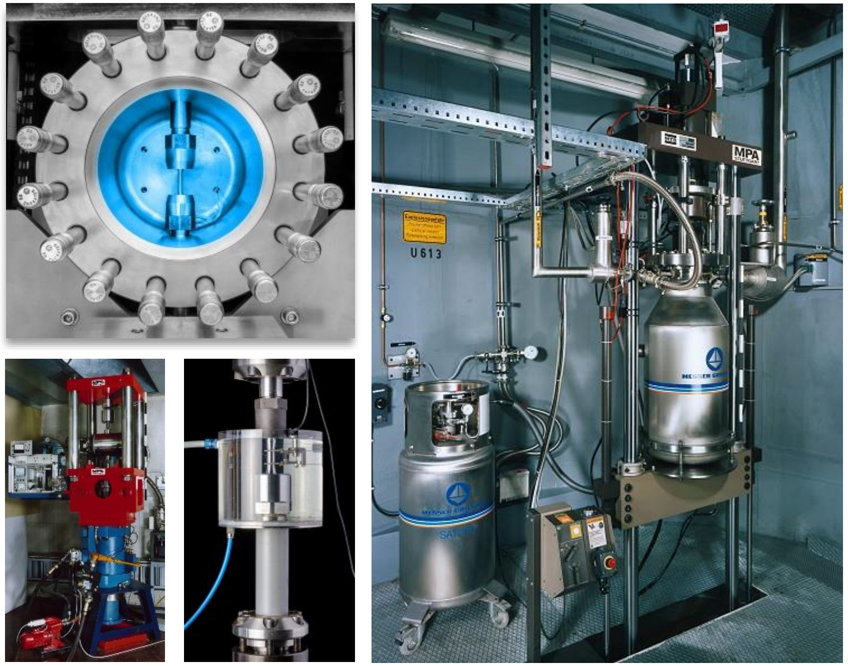
WP 3.2: Influence of hydrogen on material properties

Analysis of diffusion processes (numerical), quasi-static & dynamic testing in pressurized hydrogen atmosphere, comparison with conventionally manufactured material

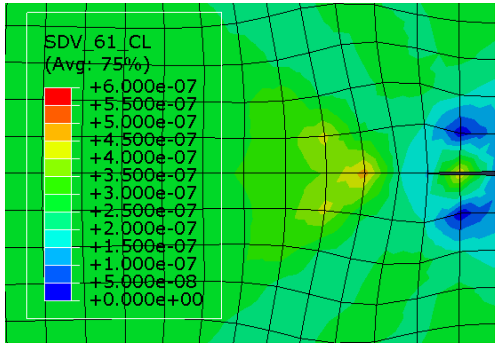
WP 3.3: Evaluation and safety assessment

Comparison of experimental data with literature, development of methods to assess the safety in hydrogen atmosphere, analyses of the influence of material imperfection, optimization of the hydrogen suitability of the additively manufactured materials (with regard to life time)

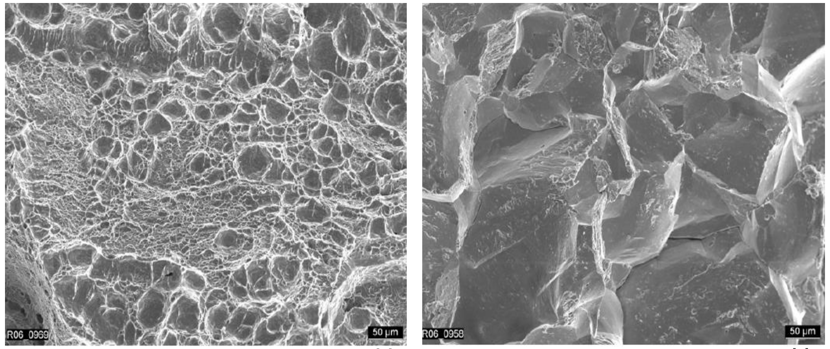
WP3: Interaction of Hydrogen with New Manufacturing Processes



Simulation of hydrogen diffusion



X3CrniMo13-4



He H_2

Testing → Modelling → Safety assesment

WP 4: Non-Destructive Testing

First-time and repetitive non-destructive detection of defects is necessary for the safe operation of machinery!

Established methods not applicable to SMRs:

- New manufacturing processes = differently oriented defects
- New reactor concepts = different damage patterns (location, size)
- Novel material composites ≠ established processes
- Very small geometries = limited accessibility

Objective:

Testing of adapted test solutions for special SMR solutions, taking into account manufacturing defects and stresses under operating and fault conditions.

WP 4.1: Identification of relevant defects

Determination of relevant flaws (production and operation) and definition of permissible/ inadmissible flaws

WP 4.2: Test methods for relevant defects

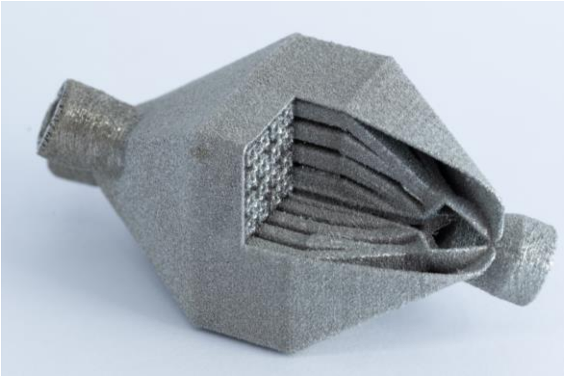
Definition and further development of NDT methods for flaws defined in WP1
Development of test solutions for safety-critical components and testing on mock-ups

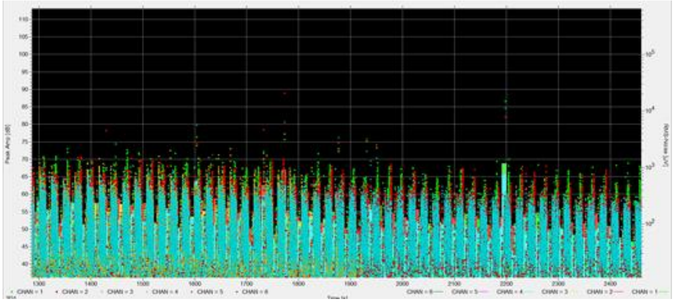
*

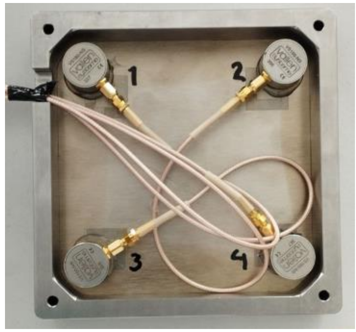
WP 4.3: Automated testing on a real scale

Raise testing solutions to a higher TRL
Adaptation of mechanized testing, e.g. via robotic systems to real-scale components

WP 4: Non-Destructive Testing







Use of different NDT methods

Inspectability of complex geometries

Additional use of in-situ monitoring

WP 5: Material behavior under high temperature-stress

Motivation:

- Additive manufacturing allows to create parts with complex geometries
- But: properties are not comparable with conventionally manufactured parts

Objective:

- Qualification of additive manufacturing material for parts in high temperature SMRs
- Development of understanding for degradation mechanisms
- Evaluation of material behaviour and adaption of existing design- and assessment-concepts

WP5.1: Experimental investigations for determination of material behaviour under relevant loading scenarios

WP5.2: Description of degradation mechanisms

WP5.3: Simulations, approaches for assement of damaging behaviour, life-time consideration

WP 5: Material behavior under high temperature-stress

WP 5.1

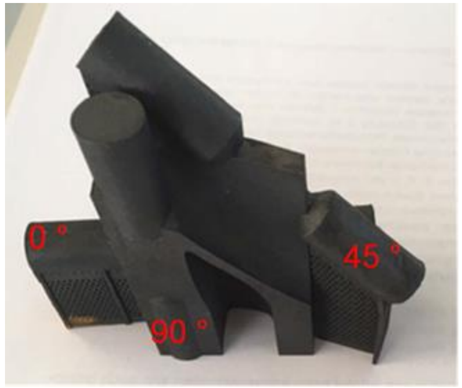
- Selection of two candidate materials with already known data from conventional manufacturing (examples: Alloy800 H, P93)
- Qualification under relevant loading scenarios: Tensile tests, LCF-tests, TFMF-tests, creep and creep-fatigue tests, crack initiation and propagation

Creep test stands

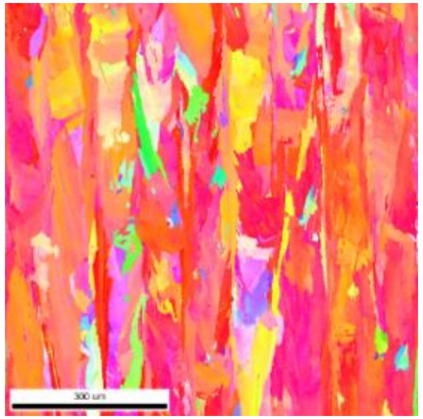
LCF-test stand

WP 5.2

- Microstructural examination for characterisation of damage mechanisms
- Examination of error behaviour and sensibility towards imperfections due to manufacturing



Generic part AM718



EBSD-image of AM718

WP 5.3

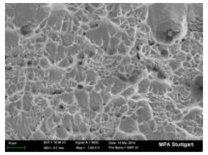
- Derivation and adaption of material laws for simulations
- Draft of assessment criteria under consideration of structural properties of material states
- Comparison with known and modified regulations
- Adaption of design and assessment concepts

WP 6: Dynamic effects under operating and loading condition

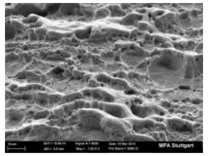
Dynamic loads in Small Modular Reactors

- Occur primarily under beyond-design-basis events and design basis accidents
- Material behavior changes due to high velocities and temperature developments

Fracture surface without adiabatic shear bands



Melting of a fracture surface due to shear localization



- Failure limits of additively manufactured specimen unknown

Objective:

Expand knowledge

Influence of additive manufacturing processes (WAAM, PBF-LB/M) on material behaviour under dynamic loading

WP 6.1: Identification and analysis of dynamic effects under operational and accident conditions

WP 6.2: Material requirements and material properties

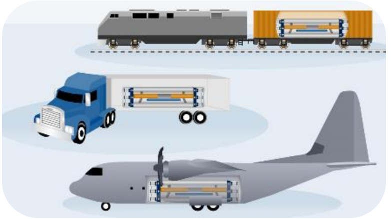
WP 6.3: Safety-critical evaluation of the components by numerical investigations

WP 6: Dynamic effects under operating and loading condition

WP 6.1

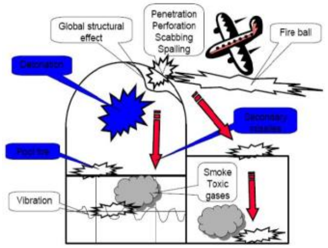
Possible dynamic load scenarios

- Crash and fall during assembly and transport



U.S. Government Accountability Office (GAO): GAO-20-380SP, 2020

- External impacts due to e.g. pressure waves or the crash of missiles

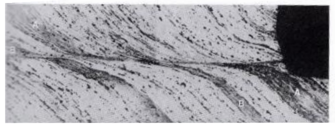


Lo Frano, R.; Forassi, G.: „Influence on aircraft impact on seismic isolated SMR reactor“, 2011

- Internal hazards (explosion) due to an accumulation of flammable gases

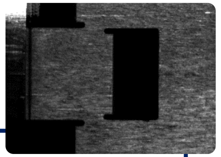
WP 6.2

- Modelling of the strain hardening and softening process of additively manufactured components



Adiabatic shear bands (2014-T6 Al) Source: „The Physics and Mathematics of Adiabatic Shear Bands“, T.W. Wrigth, 2002

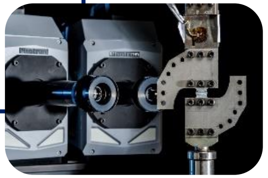
- Characterisation of the material properties



Split-Hopkinson pressure bar

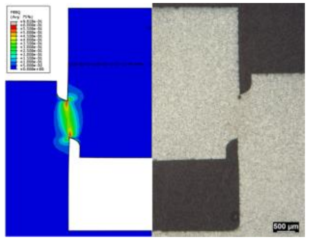
Drop-weight systems

High-speed ripping machine with high-speed camera



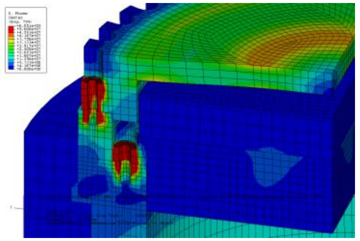
WP 6.3

- Validation of damage models



Shear failure under dynamic loading

- Simulation of components under accident conditions



Numerical simulation of the crash of a nuclear cask for the evaluation of the lid tightness

Offermanns et al. Proc. PATRAM-15 2007

WP7: Liquid metal corrosion

Heat pipe

- Passive safety concept
- Removal of fission heat from reactor core

-> Application example for LPBF-parts

- additive manufactured heat pipes with scaled dimensions for production and testing
- LPBF-material in contact with liquid potassium

assessment of Liquid metal embrittlement behaviour

- Development test stand
- Short and long term behaviour
- Determine failure mechanisms
- …

WP7.1: Corrosion behaviour and embrittlement in liquid potassium at ~700°C

WP7.2: Eperiments under liquid potassium and microstructural characterisation

WP7: Liquid metal corrosion

WP 7.1

Materials:

- Stainless steels (AISI 316, AISI 437, …)
- Nickel-base alloys (Alloy 617, Inconel 718)

Influencing factors:

- Porosity and Impurities
- Presence of mechanical loads
- Temperature gradients

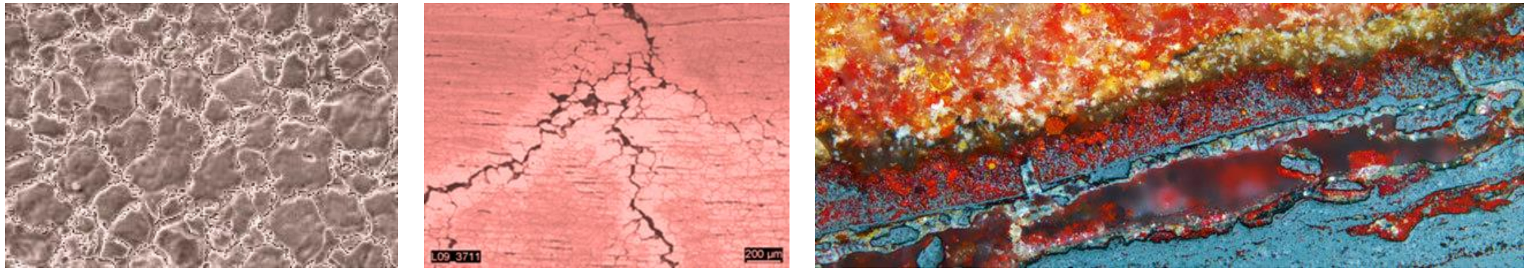
Experiments:

- Ageing experiments with and without mechanical load
- Electrochemical experiments at high temperatures

WP 7.2

Metallographic and electron microscopical investigations of following phenomena:

- Grain coarsening, precipitations, diffusion
- Liquid metal embrittlement
- Crack forming and growth
- Oxide layer formation and their chemical composition
- Porosity



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GOAL: Estabilishing a correlation between microstructural changes and corrosion mechanisms with prevention measures

Thank you for your attention!

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MPA Seminar 2023 was a great success with great speakers and debates!
The next seminar will raise the bar again:
3 days of talks in grouped sessions about different core topics.
See you in Stuttgart.

October 8th. 2024

- Hydrogen for energy revolution - materials, applications, qualification
- Advanced manufacturing for advanced applications

October 9th. 2024

- German energy revolution - challenges in plant operation and structural mechanics

October 10th. 2024

- Structural materials modelling and component integrity for safety relevant applications
- NDT of complex structures and materials

MPA STUTTGART Materials Testing Institute University of Stuttgart

SAVE THE DATE

MATERIALS PROCESSES APPLICATIONS

MPA Seminar 2024
October 8th - 10th 2024
Stuttgart

Impressions