10 Major Trends (and related questions) in Materials Science and Engineering

The common voice for materials science and technology round the world.

The global association of ca. 50 institutes in materials science and engineering.

Background

Based on an initiative of the presidential board, numerous active member WMRIF institutes have contributed and discussed the 10 most important trends for future research and development in the field of materials science and engineering.

As a common voice, these trends will continuously be updated within WMRIF and adjusted to the future development.

From 2015ff on, these trends will be freely available on the WMRIF website to get more international partners acquainted to the respective WMRIF work.

The following presentation summarizes the current 10 Trends by the MSE related key questions. Personal comments and contributions are regarded as extremely valuable and everybody is cordially invited to contribute and a forum for member institute comments will maintain topicality.

The current version represents a draft only for personal use with exemplary illustrations and is subject to changes based on the discussion among the member institutes during the 6th WMRIF General Agenda.

Identification of Trends

Consideration of OECD Global Grand Challenges

BETTER POLICIES FOR BETTER LIVES

Energy	Climate Change	Global Health	Agriculture and Food
Security and Safety	Mobility	Housing	Communi-cation

Reflection at regional activities

.....

… require Materials
to withstand extreme and varying service conditions and loadings at designed technical components, structures and systems

… represent the roots
for future trends in Materials Science and Engineering

Identification of the Trends

Are 3 trend-setting factors complied ?

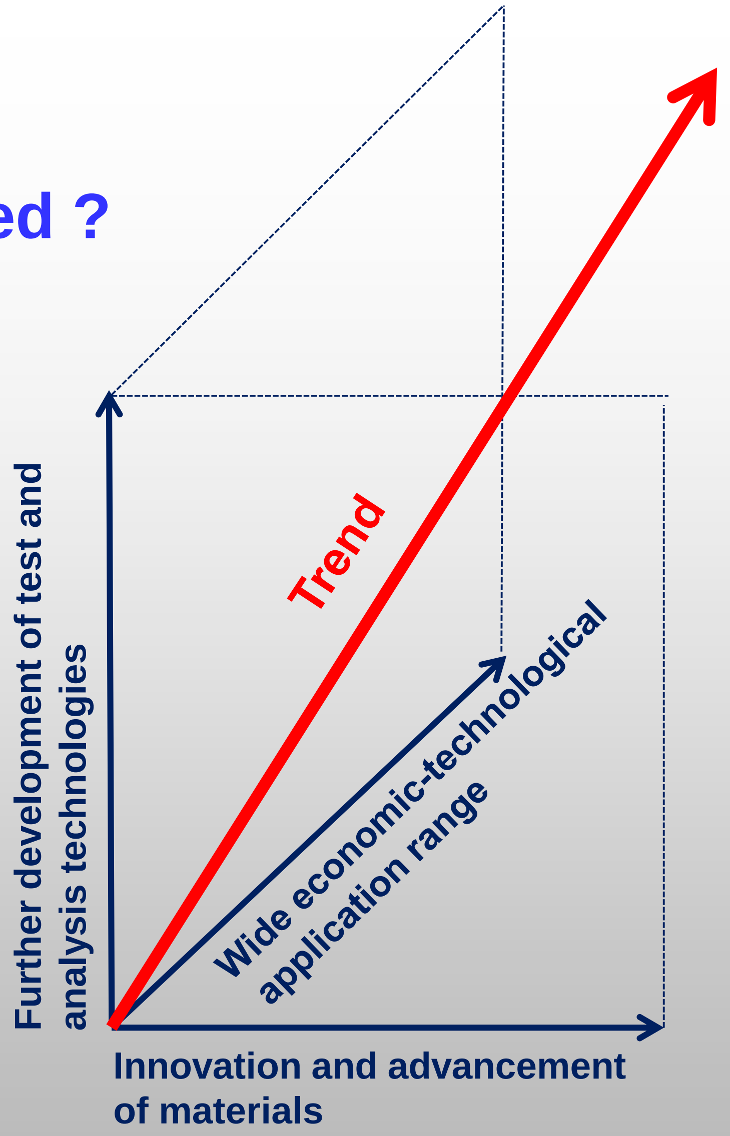
Is there agreement among the WMRIF institutes that it is really a trend ?

~~Modelling and simulation in MSE~~

Tool, less a trend

~~Nanotechnology in MSE: Nanomaterials and Nanostructuring~~

Subgroup in the needs, less trends



10 Major Trends (and related questions) in Materials Science and Engineering (MSE)

Directly related to the grand global challenges

Materials challenges for…..

1. **Renewable energy and energy storage**
2. **Transportation and mobility**
3. **Sustainable buildings and infrastructure**
4. **Medical technologies and biological functionalization**
5. **Managing climate change and natural catastrophes**

Indirectly related to the global challenges

Materials related issues to…..

6. **Rapid design and manufacturing**
7. **Recovery and usage of scarce resources: Elements, minerals and materials** including limited market availability and substitution
8. **Potable water retrieval, supply and purification**
9. **Lifetime extension and long term service of technical systems and their components**
   including revolution of service life evaluation procedures, materials modelling
10. **Deeper insight into materials degradation mechanisms and data mining**
    including revolution of materials analysis and testing procedures, across the scales: from atomic to field tests, in-situ detection of effects, thresholds

1. Materials challenges for renewable energy and energy storage

Energy

→ Solar energy:

- How can solar cells be designed cheaper, more mobile and more efficient and how can nano-materials contribute to this ?
- How can the fire safety of solar cells be increased by decreased flammability of materials, reduced emission of hazardous substances as well as improved protection of fire brigades, citizens and the environment ?

→ Offshore wind turbines:

- How can the material related behaviour can best be assessed for components subjected to extreme and coupled loads in harsh environments ?
- Do we have the welding procedures for efficient joining of large scale mast components ?

→ Tidal power plants:

- Do we really understand the mechanisms to achieve substantial prevention of marine and microbiologically induced localized corrosion ?

Photo: B. Wolters/Leer (Baulinks.de)

© Freiwillige Feuerwehr Hochstadt

SAW of offshore components (TUB)

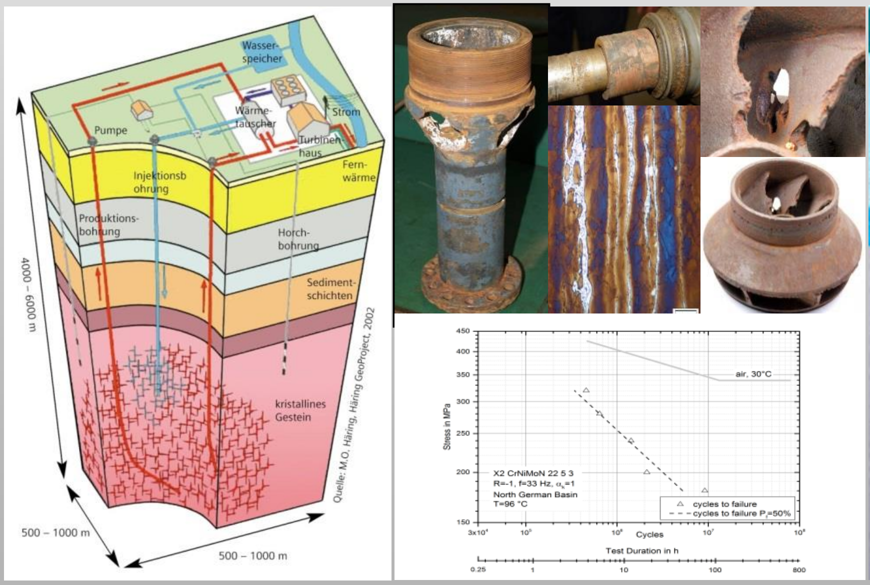
→ Geothermal power

Materials are subjected to extreme coupled loads:

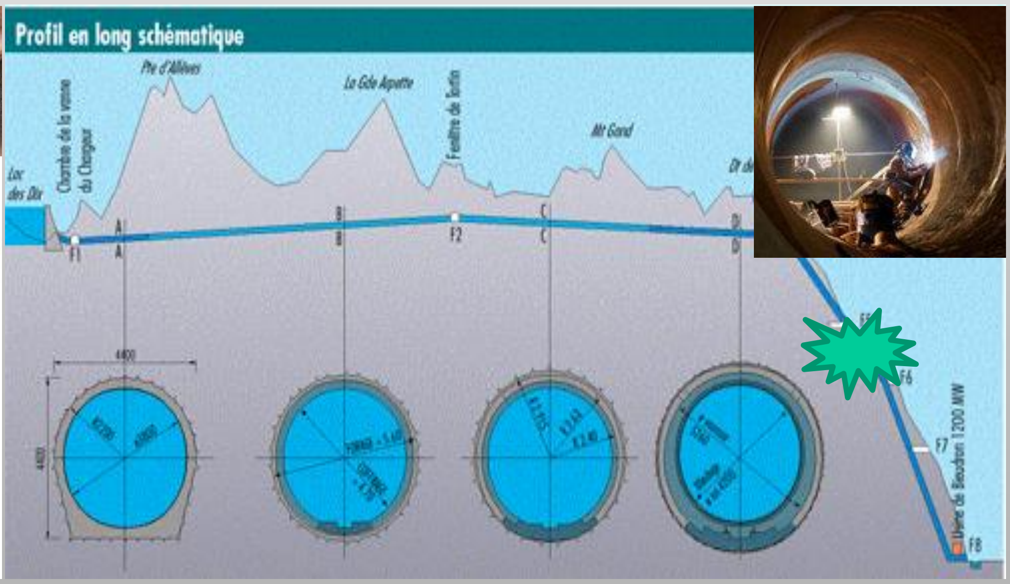
- Do we have suitable test procedures to determine reliable threshold values for erosion corrosion and corrosion fatigue in such harsh environments ?
- Can we improve the materials to increase the sustainability of the components ?
- How do we have to adjust the life time assessment procedures ?
- Do we have to re-consider the risk based inspection procedures ?

→ Hydro power plants

- How can we avoid hydrogen assisted cracking and further disasters during fabrication welding and service start-up of high strength structural steel tubulars ?



Erosion corrosion and corrosion fatigue at geothermal power pumps (BAM)



Location of fractured down-pipe at hydro power plant Cleuson Dixence in 2000 and successful recommissioning in 2010

→ Long distance energy transmission:

- How can we enhance research on super conductors ?
- How can we improve high strength materials for masts and equipment of power transmission lines to withstand the loads resulting from climate changes ?
- Can we include climate changes in the standards for power transmission lines ?

→ Energy waste management and sustainable energy storage:

- How can we improve the materials for more efficient energy conversion and for insulation ?
- How can we increase the long term storage capacity of batteries ?
- How can we minimize accidental risks for batteries in cars and houses ?

Test set-up to investigate the fatigue resistance of batteries (BAM)

Test set-up to investigate the fire resistance of batteries at accidental penetration (BAM)

Failure of power line masts caused by extreme ice packages (BAM)

1. Materials challenges for renewable energy and energy storage – cont´d

Energy

→ Conventional/fossil fired power plants

- How can we realize that the materials for fossil fired power plant components resist higher operation temperatures and much more frequent start-up/shut-down cycles at the same time ?
- Do we have sufficient in process monitoring of materials degradation during long time higher operation temperatures ?

Corrosion 70 (2014), No. 6, pp. 563 – 578

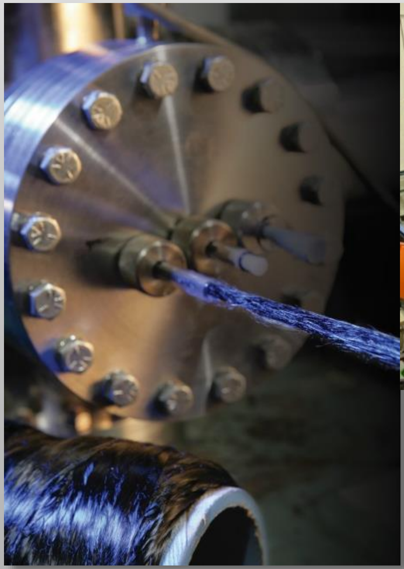
Fossil fired power station boiler tube wall (dguha1952.blogspot.com), hydrogen assisted cracking at welded tube section (BAM) and investigated specimens (ISSV)

1. Materials challenges for renewable energy and energy storage – cont´d

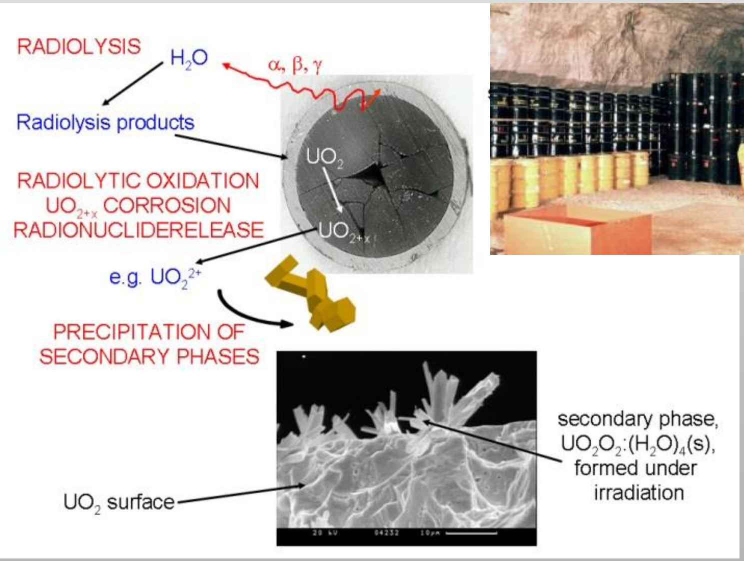
Energy

→ Nuclear power plants and nuclear waste management

- How can we develop new materials which can sustain irradiation damages ?
- Do we have processes to weld such materials and is there a need to develop new weld qualification tests ?
- What results and experience can we gain from tear down analysis and respective testing of long-term used materials for avoidance of any further nuclear power plant disaster in future ?
- Do we have reliable procedures for accelerated testing of the crack and corrosion resistance of nuclear waste material and respective containments subjected to aggressive saline environments for thousands of years ?



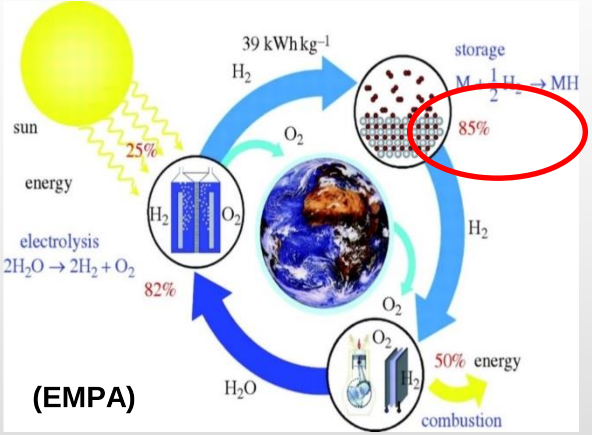
Fiber and composite materials for nuclear applications (ORNL)



Corrosion mechanims of nuclear fuel pellets (ine.kit.edu)

→ High pressure storage of gases

- How can we improve the materials to increase durability of high pressure storage ?
- How can we improve the materials with respect to technical safety at accidental, explosion and fire scenarios ?

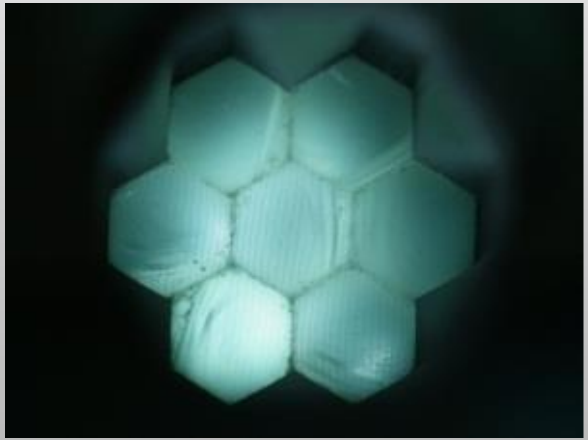


(EMPA)

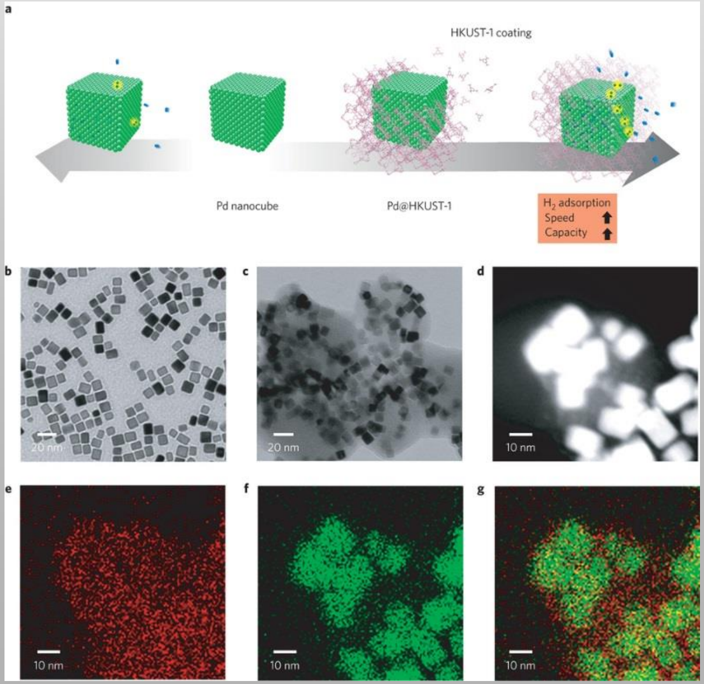
→ Special emphasis: Hydrogen

- Which alternative materials to CNG containers can be developed for hydrogen storage ?
- What degradation of materials applied to components for hydrogen transport and combustion might happen?

CNG container and respective fatigue test set up (BAM)



Glass capillaries for hydrogen storage (CEn, BAM)



Enhancement of hydrogen storage capacity and speed in palladium by applying a metal-organic framework (MOF) coating to cubic Pd nanoparticles
(Li et al.: Nature Materials 13 (2014), pp. 802 – 806)

→ Public and mass transportations systems

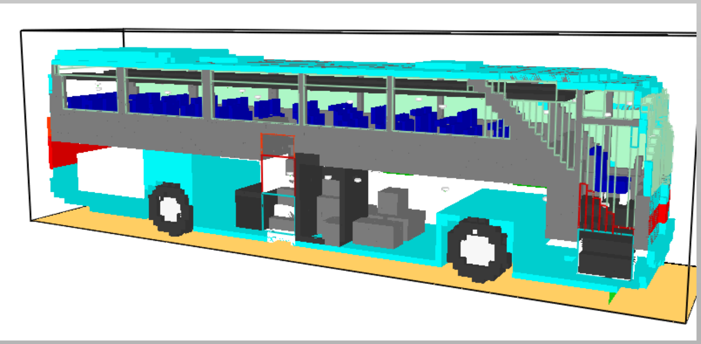
- How can the fire safety be increased in trains, ships planes, busses and cars ?

→ Multimaterial mix and joining processes

- How can the various materials (steel, Al, Mg, Ti) be joined ?
- How can we weld UHSS and maintain the properties at the welded joint ?
- How can crash/impact loads be transferred from one material class to another (metals, polymers, CFK, ceramics, textiles) ?
- Do we have adequate NDE to evaluate joints of dissimilar materials ?

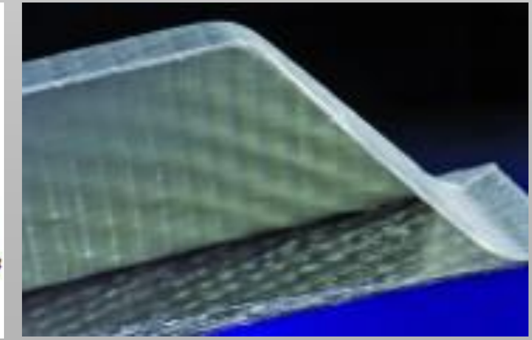
→ Increasing efficiency

- How can friction be reduced in combustion engines ?
- How can the various advanced engine concepts be realized ?



Simulation of the fire and smoke distribution in a travelling bus (BAM)

Goede et al.: Eur. Transp. Res. Rev. 1, pp. 5 – 10



Laser welded and cut CFK profile (FhG-ILT)

→ Fire resistance of buildings and tunnels

- How can the fire resistance of wall insulations be increased ?
- How can the various procedures for mathematical modelling of fire and smoke distribution at built infrastructure be coupled (CFD with FEM etc.) ?

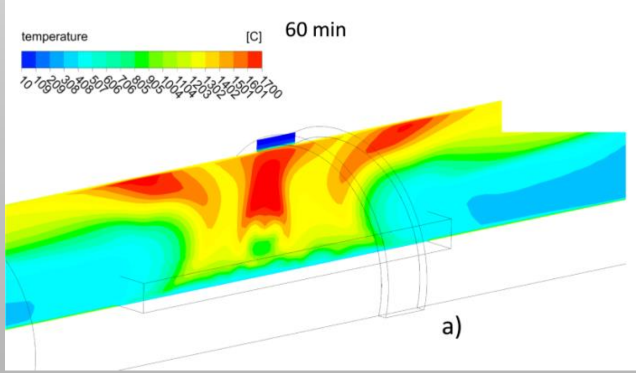
→ New green building materials

- How can the novel building materials be applied ?

→ Ageing of buildings and infrastructure

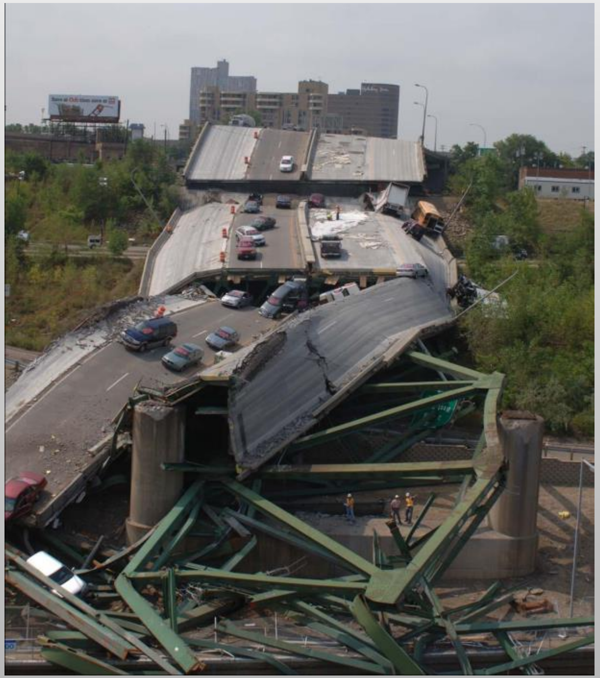
- How can the usage duration economically be extended ?

Novel corrosion resistant reinforcing steel (NIMS)



Coupled CFD and FEM simulated fire distribution in a street tunnel (BAM)

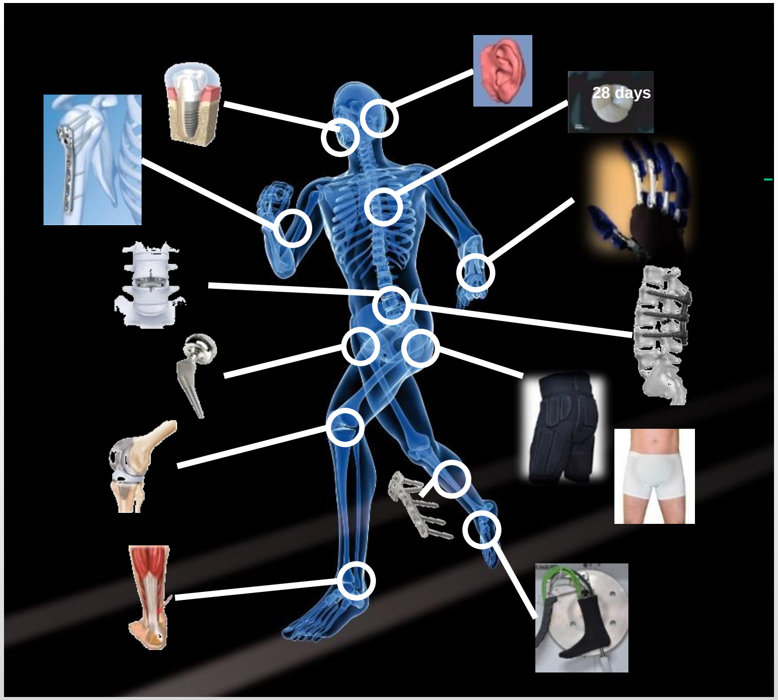
Fire at polystyrene insulated front of a residential building (www.feuerwehr.de)

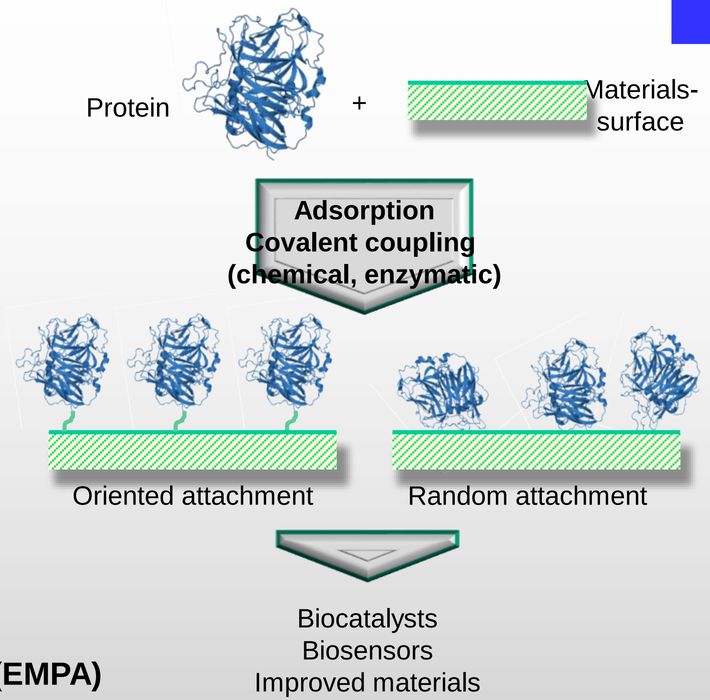


I 35 bridge failure initiated by crevice corrosion (NTSB – USA)

4. Materials challenges for medical technologies and biological functionalization

Health





(EMPA)

→ Medical technologies

- Which materials for supporting or maintaining body functions have still to be developed under consideration of the ageing societies ?
- Which material properties are most important for long term use in the human body?
- How can we avoid failures in the specific environment (body fluids)?
- Which materials are suitable for temporary human body applications and subsequent resorbing without removal by additional surgery and how can we quantitatively control such resorbing of materials?
- Which EHS aspects have to be covered during development of new materials and applications ?

Health

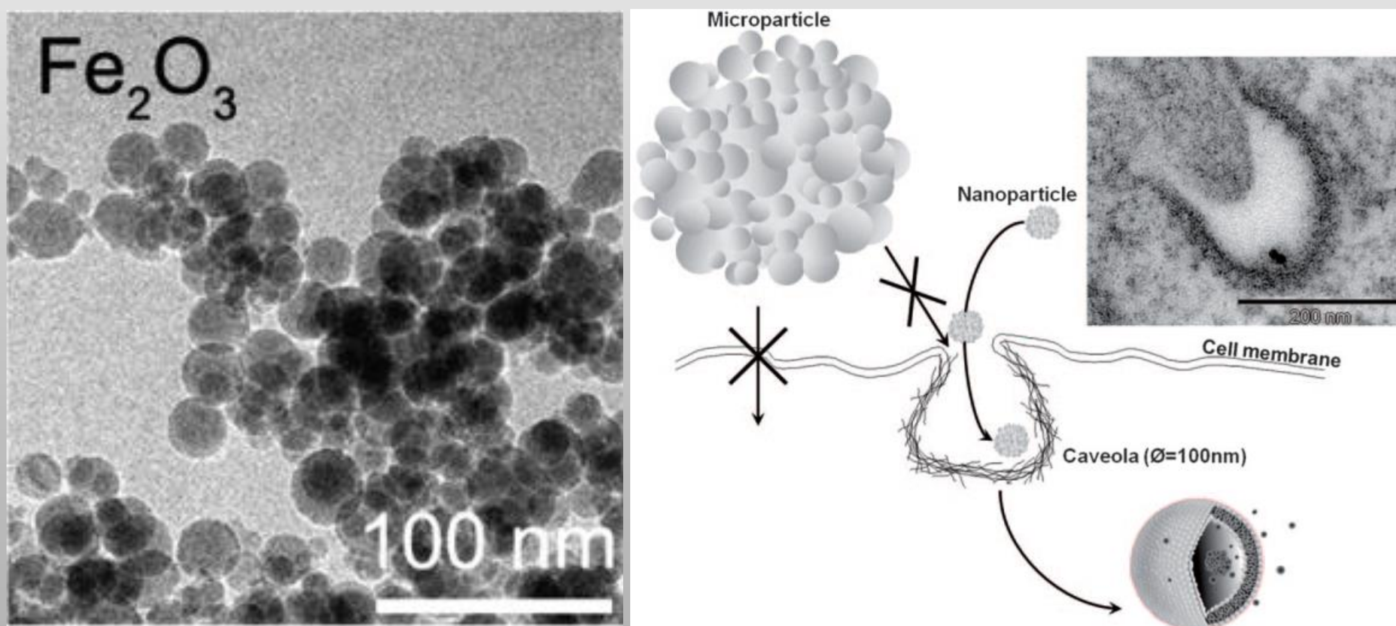
→ Biocompatibility and biological functionalization of nano-materials

- Which risks are really evolving from nanoparticles, e.g. interaction with and resorption at biological membranes ?
- Are we hyping the effects ?
- Which hazards are evolving from nanoparticles, e.g. structure and element analysis of respirable dust?

Fullerene (C60)
SWCNT
MWCNT
Nano silver
Nano iron
(Carbon Black)
Titanium dioxide
(Aluminium oxide)
Cerium oxide
Zink oxide
Silicon dioxide
(Polystyrol)
(Dendrimere)
(Nano clays)

Contributor
Co-Sponsor
Lead Sponsor

OECD: Toxicological evaluation of 14 nano materials (BMU Directive)



The Trojan-Horse Transport Principle, H.F. Krug & P. Wick: Angew. Chem. Int. Ed. 2011, 50, 1260 ff. (EMPA)

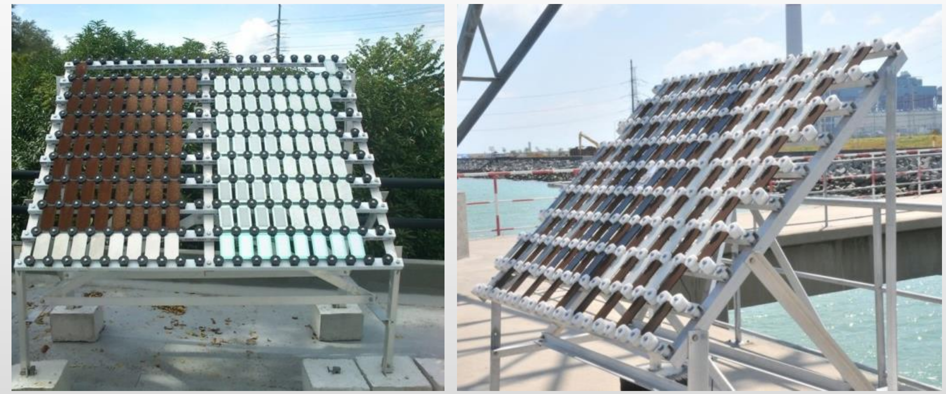
5. Materials challenges for managing climate changes and catastrophes

Climate Change

→ Climate changes significantly affects the long-term service behavior of materials, especially atmospheric corrosion rates

- Which materials resist increased atmospheric corrosion in marine environments ?
- Which materials can we develop to cope with the climate changes ?

Test sites for studying climate effects on atmospheric corrosion of carbon structural steels in Thailand (MTec)



Exposure test of steel specimens in tropical climate (MTec)

Larger aggression of marine waters due to climate changes entail significant corrosion in the splash water zone of high-power transmission systems (MTec)

5. Materials challenges for managing climate changes and catastrophes

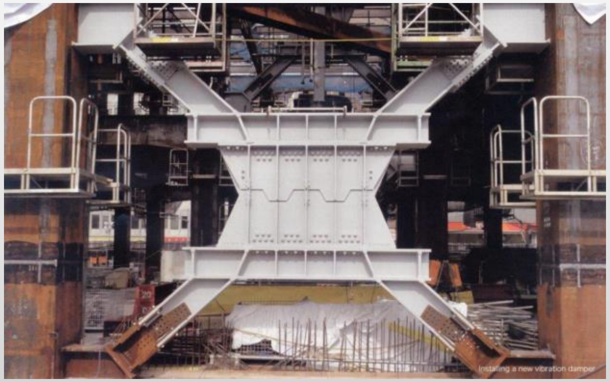
Climate Change

→ Carbon Capture and Storage

- Which materials are required for CO_2 capture conversion ?
- Which test procedures are suitable to address long-term service behavior of CO_2 storage components ?

→ Resistance against extreme loading

- How can accelerated corrosion be prevented and how do we mitigate the difficulties to weld newly developed corrosion resistant alloys ?
- How can extreme loads due to natural catastrophes be coped ?



Installation of an earth quake damping device for a building in Japan (NIMS)

→ Reduction of pollution

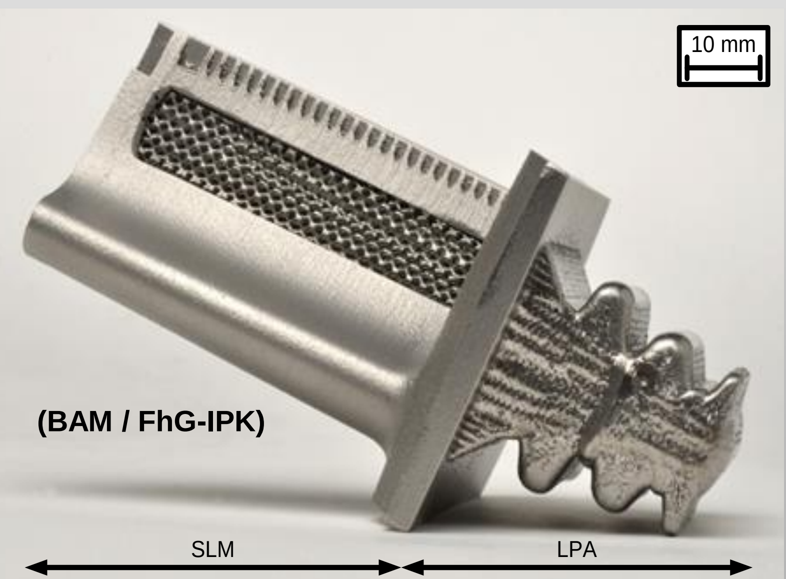
- Which materials can be developed to increase the efficiency and temperatures of waste-to-energy plants to reduce polymer pollution ?
- Which materials can we develop that lead to a reduced carbon-footprint ?
- Do we know the nano-hazards of polymer pollution ?
- Do we understand the ageing and decomposition of polymers completely to combat polymer pollution ?

Polymer parts in organic waste of households (BAM)

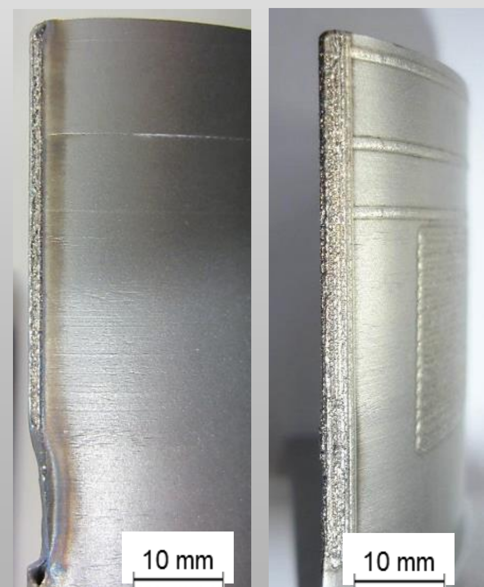
Samples of polymer materials taken from organic waste / compost and prepared for lab investigations (BAM)

→ Additive / rapid manufacturing processes:

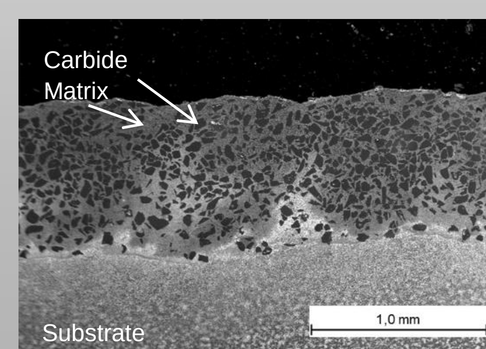
- How can we optimize the processes parameters to achieve isotropic and homogeneous material properties in additive manufactured components ?
- How can we address other markets than aerospace for additive manufacturing ?
- How can we avoid cracking initiated by rapid metallurgical phenomena and loads ?
- Do we understand the physical, chemical and mechanical behaviour at the interfaces between substrates and coatings at additive manufactured components ?
- Can we apply the same heat treatment procedures used for conventional produced components to additive manufactured components ?



Combination of Selective Laser Melting (SLM) and Laser Powder Welding (LPA) for turbine blades



Repair of a turbine blade edge by Laser Powder Welding (LPA)



Wear resistant TiC layers by Laser Powder Welding (LPA)

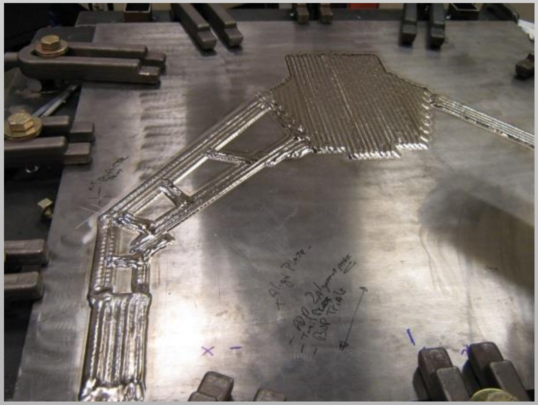
6. Materials issues related to rapid design and manufacturing

→ Additive / rapid manufactured components:

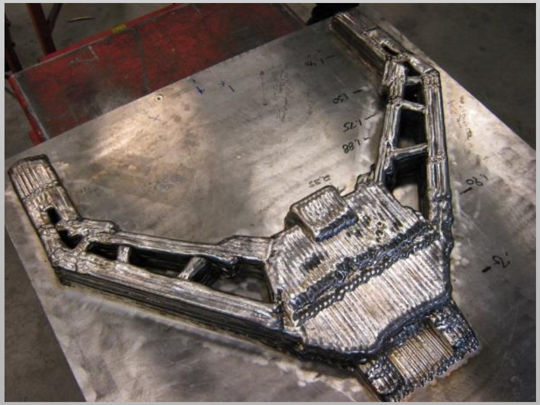
- How sustainable are additive manufactured repair and replacement parts in comparison to conventionally produced ones ?
- Do we have substantial test and evaluation procedures to investigate the long term service behaviour of additive manufactured components ?
- How can we join additive manufactured components to other parts of a structure ?
- Can the materials behaviour at extremes be controlled for effective and efficient processing and manufacturing ?
- How can we repair (welding) additive manufactured components ?

Size capabilities of additive manufacturing from single beads stacked upon each other (blades) to large dimensions at high deposition rates (rotors) (EWI)

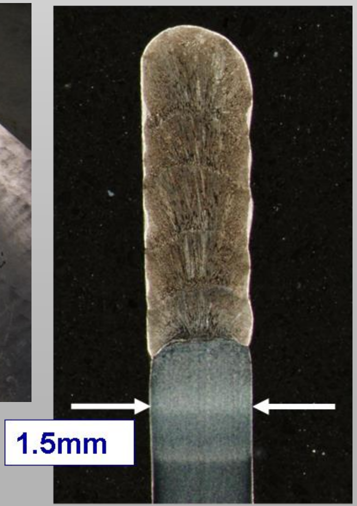
GTAW (Hot Wire)



First layer



Completed deposit



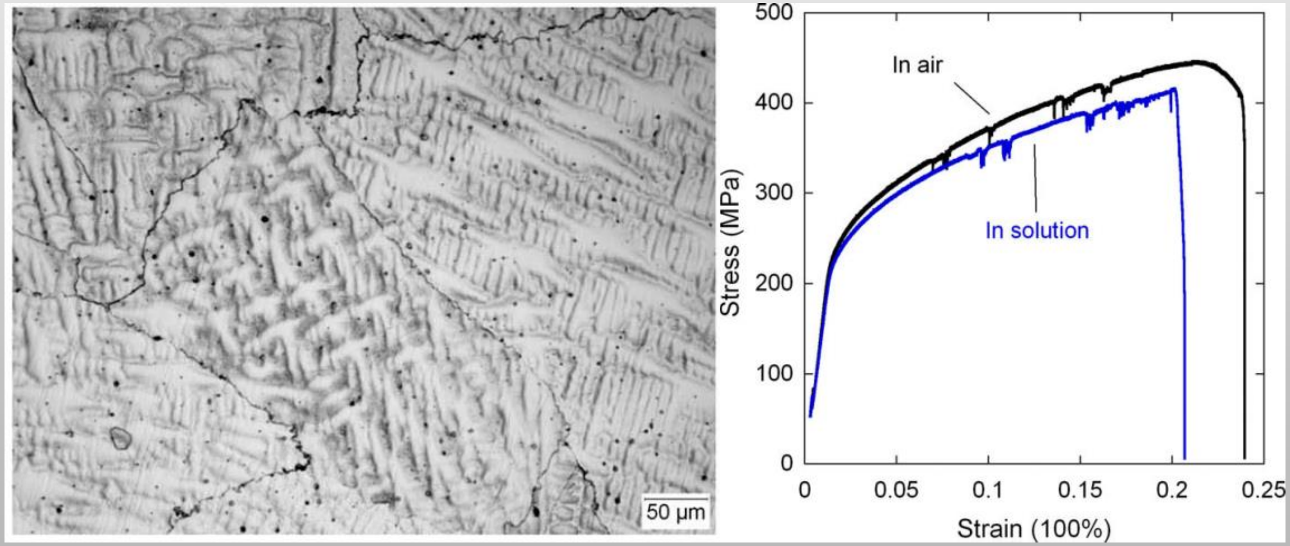
PAW (Cold Wire)

Additive manufacturing with arc welding:
GTAW-HW of a Ti 6 4 vehicle control arm on a 4´by 4´plate (Photos provided courtesy of EWI)

7. Materials issues related to recovery and usage of scarce resources: Elements, minerals and materials

→ Usage of scarce resources

- Which quantities of rare elements, minerals, materials are globally justifiable for improvement of mass material properties ?
- Which substitutes provide the same material properties in a specific component ?
- How does market availability affect fitness for purpose requirements affect the selection of materials ?
- Structural materials designed for very specific applications are often only limited available and rest batches usually cannot be used for other purposes …..



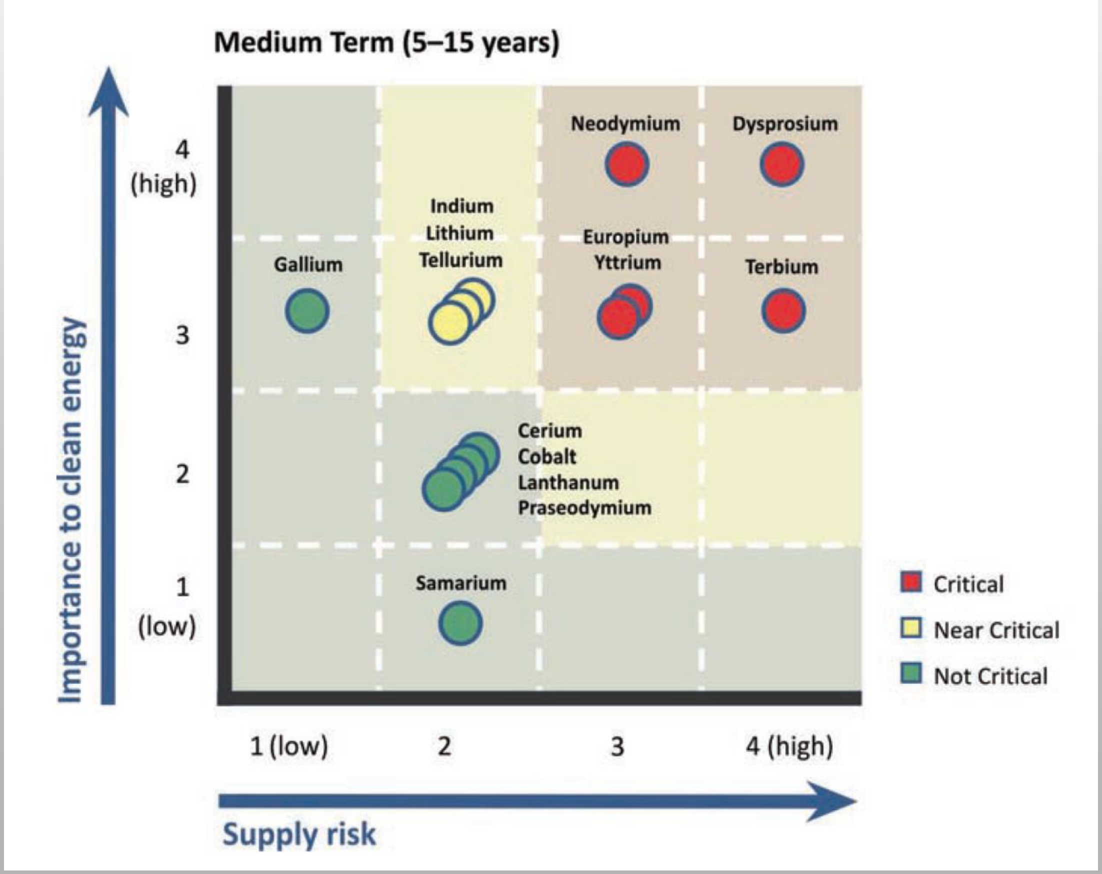
Ru > 1 wt.-% significantly improves the SSC resistance of Ni-Cu welding fillers for AISI 304 SS (Liang et al.: Corrosion Science 52)

7. Materials issues related to recovery and usage of scarce resources: Elements, minerals and materials

→ Recovery and substitution of scarce resources

- Which procedures can we develop to separate scarce materials during recycling more efficiently ?
- How can we substitute rare or toxic substances and materials, in particular for electronic devices, by development of novel materials ?

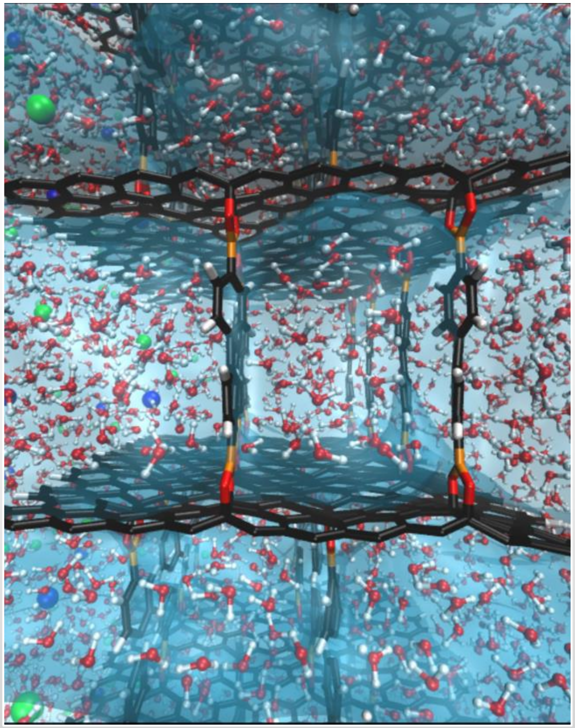
Mid-term critical supply of the sector renewable energy with rare elements (US-DOE)



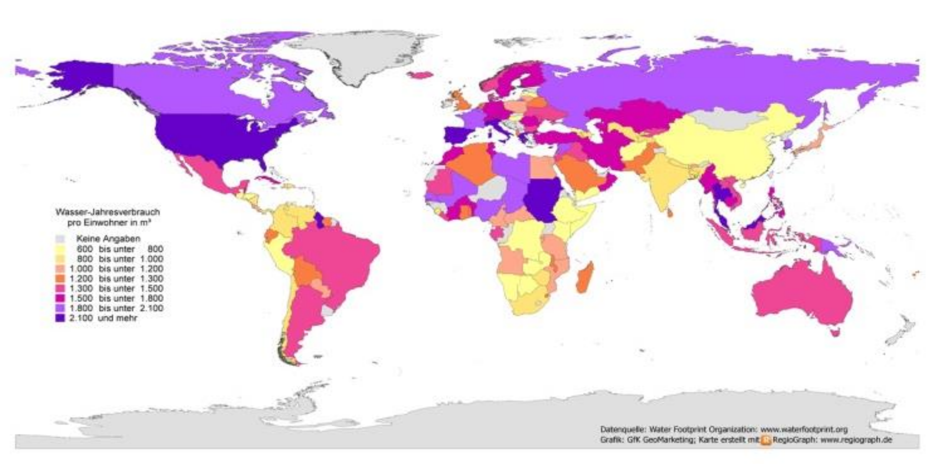
http://energy.gov/sites/prod/files/edg/news/documents/criticalmaterialsstrategy.pdf

→ Materials for potable water retrieval and supply

- How can we avoid potable water contamination by emissions from materials during processes, manufacturing and usage, especially by corrosion ?
- How can we avoid corrosion leakages in the potable water supply chain ?
- Which materials have to be developed for more simple and cost-effective water cleaning processes ?
- Which materials have to be developed for filter systems to improve used water Treatment systems with respect to purification and sustainability ?



Large-scale molecular dynamics simulation to assess the performance of graphene oxide framework membranes for water purification (ORNL)



Water consumption (>water footprint<) of the nations in m³ per inhabitant

Leakages and corrosion of potable water pipes

9. Materials issues related to
long term service and lifetime extension of technical systems and their components

New technical systems – faster, higher, stronger (for less money!)

- > **Innovative Materials**
- > **Nano structuring**
- > **Multi material mix**
- > **Light weight design**

Research requirements (a. o.)

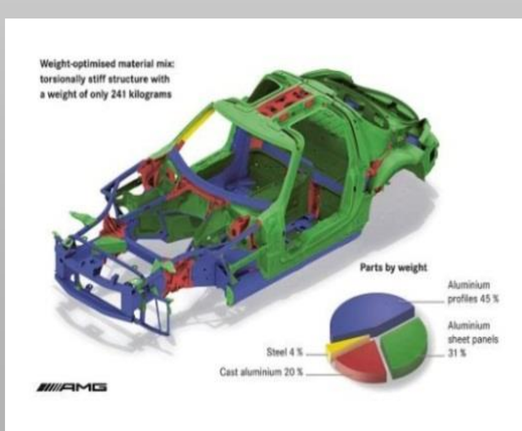
- Test procedures for determination of the material behaviour and threshold values under real coupled loading
- Test procedures for investigation of the interaction between different materials in the same component or structure

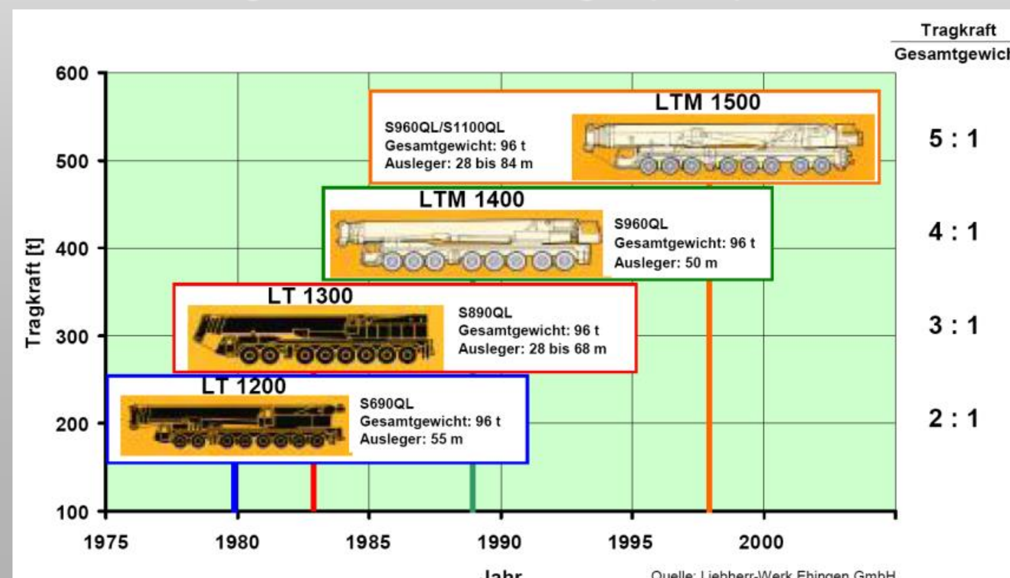
Existing technical systems – extended use (for the same amount of money!)

- > **Life time extension**
- > **Health monitoring**
- > **Risk based Inspection**
- > **Preventive repair**

Research requirements (a. o.)

- Test procedures for complex long term loading and investigation of the last 10% of the product life cycle
- Modification of test procedures for consideration of the exceptional loading conditions during repair procedures

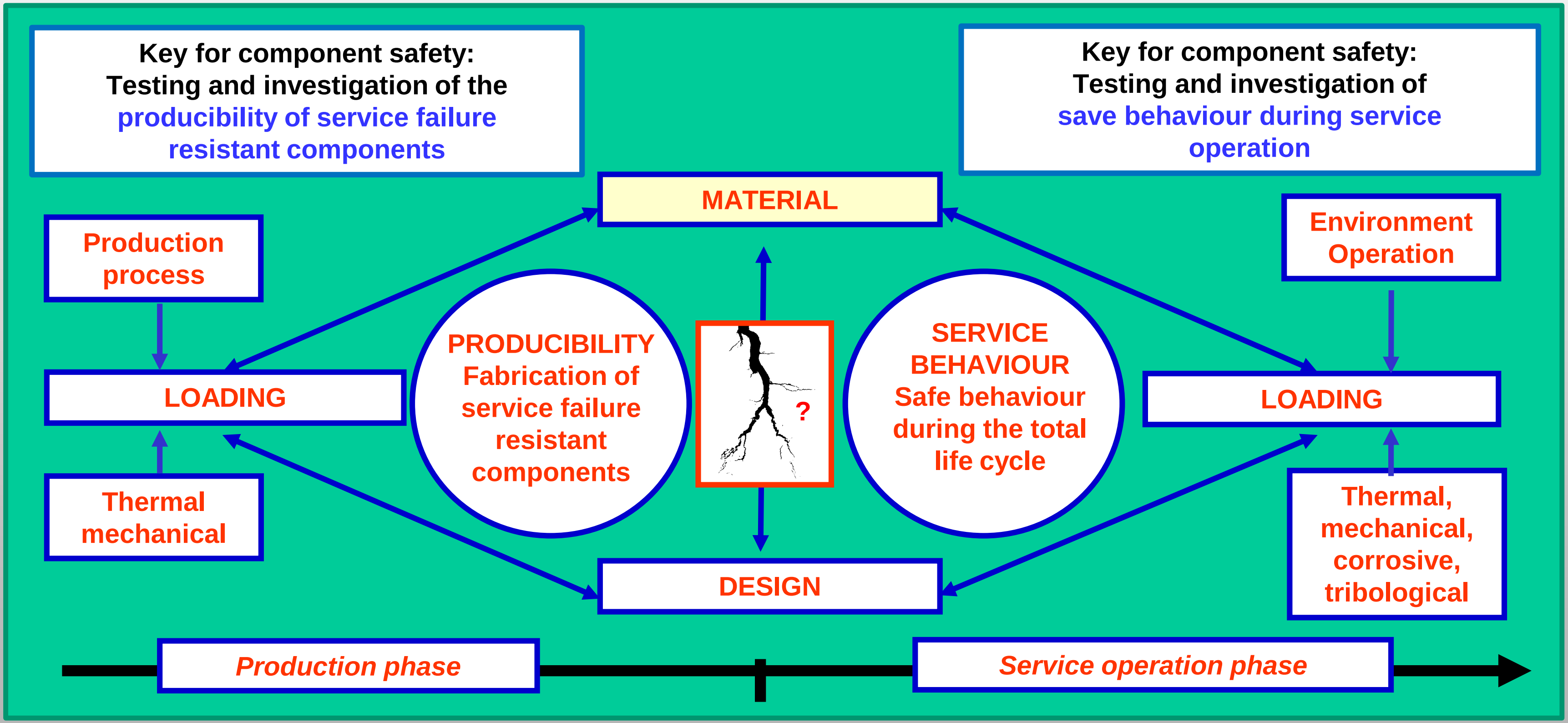




9. Materials issues related to
long term service and lifetime extension of technical systems and their components

→ Development of materials testing towards better life time evaluation procedures

- Which life time assessement procedures do we have that take into account the influence of loads and defects introduced during production on the service life ?
- How can we improve life time assessment procedures to consider coupled and extreme loads (acting at the same time and location on a component) as well as multi material mix ?

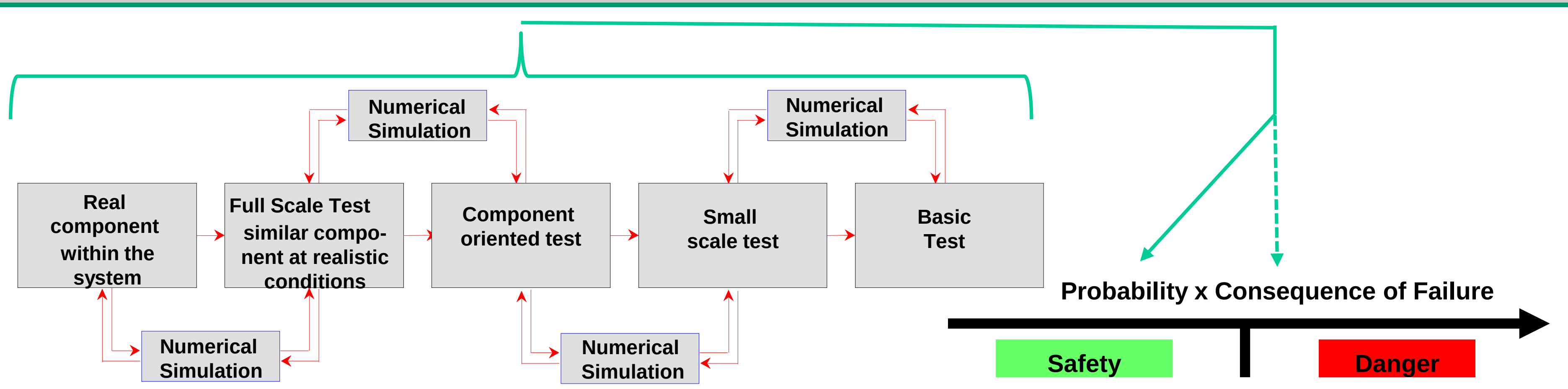


Interaction of producability and service behaviour of components:
Driven by the interaction of material, design and loading (Springer Handbook of Technical Diagnostics, Chap. 17)
→ Failure resistance / Component safety: Load bearing capacities of all materials at all locations in a specific component are larger than the actual loads during the complete duration of production phase and the usage duration

9. Materials issues related to
long term service and lifetime extension of technical systems and their components

→Development of materials testing towards better life time evaluation procedures

- How do material defects in innovative high strength materials affect the long-term resistance of components and structures against failures ?
- How do the threshold values and the fatigue strength of components vary towards the end of the product life cycle under coupled loading (@ > 10^9 cycles) ?
- How can real loading conditions be transferred to laboratory testing and vice versa and which parameters are suitable ?
- How to develop materials testing towards a systems and component testing combining complexity and scale to the best economically feasible gain of knowledge, also for quantitative risk analyses ?
- How to efficiently and economically combine micro systems technology, analytical procedures and in-situ monitoring in modern materials testing procedures ?



Sound combination of test procedures (ThB –BAM)

9. Materials issues related to
long term service and lifetime extension of technical systems and their components

Innovative materials used at the limits of their design properties are prone to failure upon small deviations in structure and composition (BAM)

Avoidance of metal-water reactions reduces the risk by development of large amounts of hydrogen and explosive gas mixtures (Sheperd – CalTech)

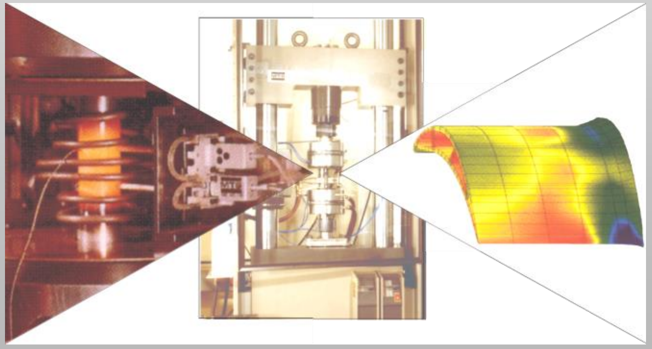
→ Learning from failure analyses and disasters

- How can knowledge from failures and catastrophes be effectively transferred to R&D work to prolong service life time ?
- How can experience from damage and failure analysis be transferred to standardization and providing expert advice to industry, policy and public debate ?
- How can WMRIF institutes‘ competence be made available in major national and international disaster ?
- How can global standards in damage analysis and failure analysis procedures be improved?

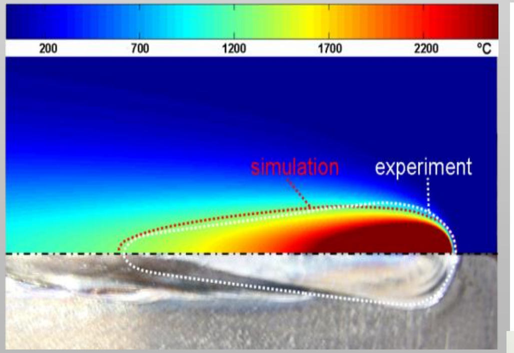
9. Materials issues related to long term service and lifetime extension of technical systems and their components

→ Materials Informatics I: Modelling and simulation achievements

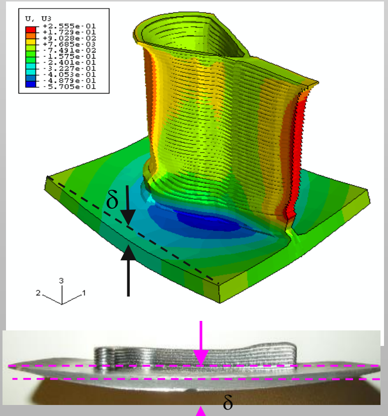
- How can materials modelling and simulation become an integrated part in the life time assessment procedures for technical components and systems ?
- How can the various simulation scales be coupled to each other ?
  Bridging the gaps between the atomic scale and the real component
- How can simulation and experiment can be validated by each other ?
  Identification of the parameters with the largest influence on the results
- How can the models be validated to improve the quality of nondestructive testing ?
- How can we mitigate the challenges associated with modelling of welding materials (advanced models for grain growth, microstructure formation and properties) ?



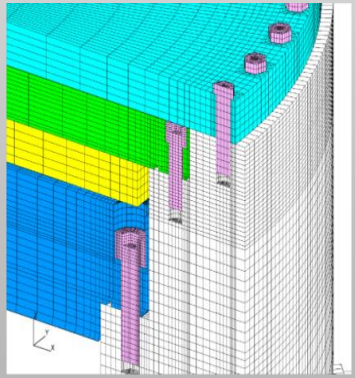
Simulation of thermal-mechanical loading of a turbine blade (BAM)



Validation of calculated temperature distribution during welding (BAM)



Qualitative comparison of weld distortion during AM (Photo provided courtesy of EWI)

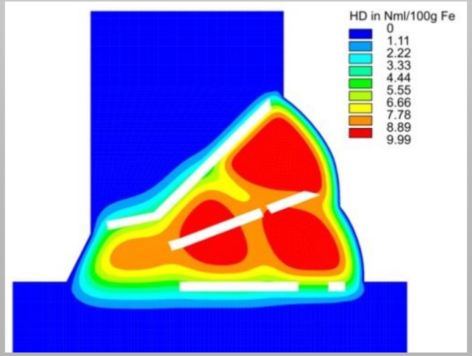


FE grid of a Castor lid sealing (BAM)

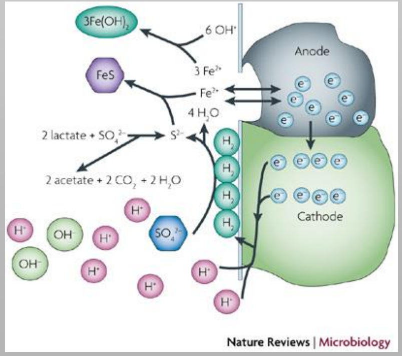
10. Deeper insight into materials degradation mechanisms and data mining

→ Advanced structural materials

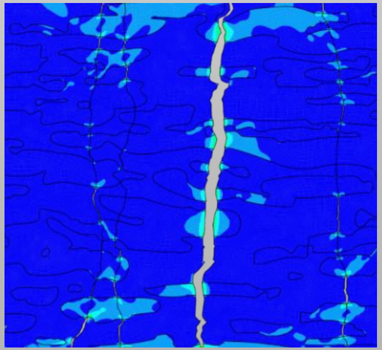
- Do we really understand the real damage mechanisms under coupled loading, as for instance for SCC, CF, TMF, reheat and hot cracking ?
- Do we understand the behaviour of materials under extreme loading conditions of radiation, pressure, strain, temperature and chemical reactivity in detail to allow new materials to be predicted, synthesized, processed and ultimately designed ?
- Which threshold values are required with respect to realistic coupled loads, and are these sufficient to describe the real loading capacities ?
- How do material properties and threshold values change after unforeseen loading events and extreme conditions, as for instance after fire or explosion?
- Which contribution does numerical modelling provide for elucidation of failure mechanisms as well as to the determination of failure origins ?
- How does increased nano-structuring of materials affect the materials properties and how can this be transferred to components ?



Hydrogen distribution and cracking in a multi-layer butt weld (BAM)



Biogenic corrosion

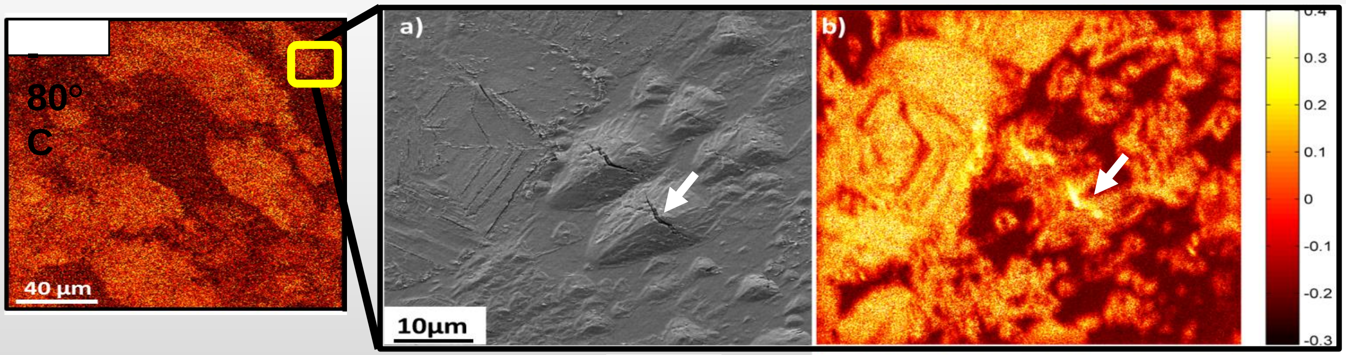


Hydrogen assisted cracking in DSS microstructure (BAM)

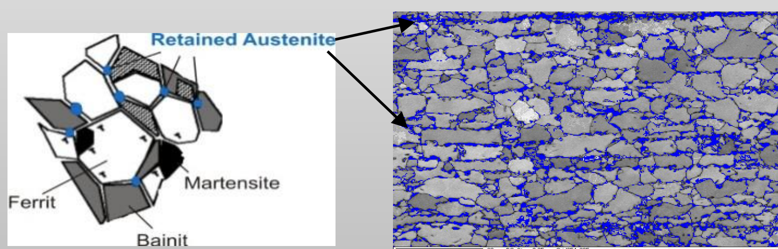
10. Materials issues related to
Deeper insight into materials degradation mechanisms and data mining

→ Significant achievements in materials analysis techniques

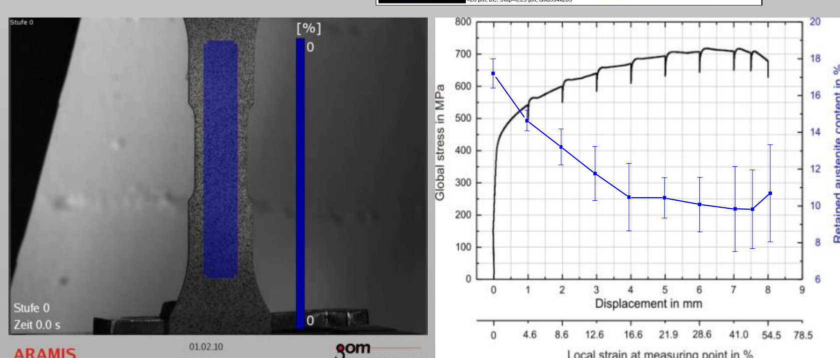
– How can improved materials measurement procedures contribute to the clarification of damage mechanisms and determination of threshold values ?

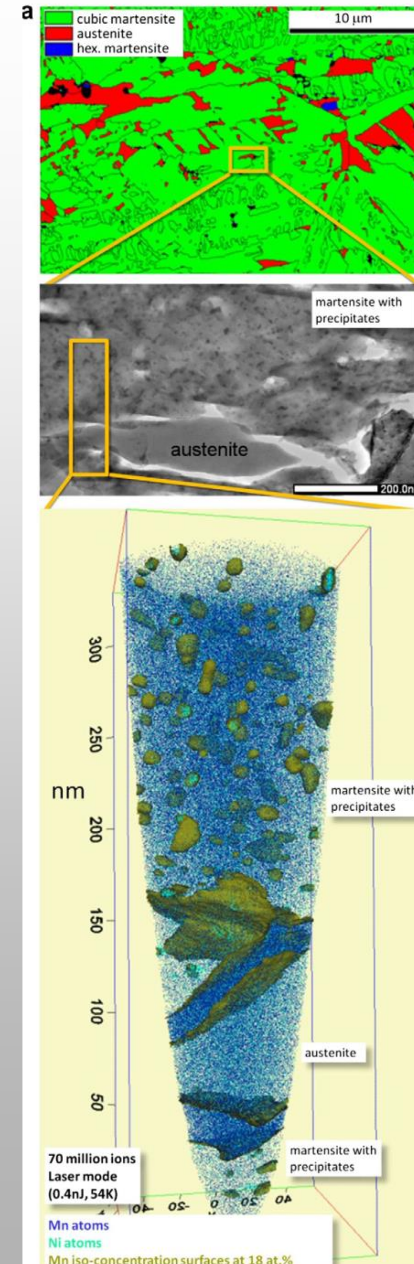


In-situ detection of deuterium at twins in the ferrite of DSS by TOF-SIMS (BAM)



Verification of the steel TRIP-effect by synchrotron radiation experiments (BAM)





Laserpulse-Atom-Probe-Tomography, Element- and microstructural changes in an austentic Mn-TRIP-steel (Dimitrieva, Raabe et al.: Acta Mater 59 (2011), 364ff)

10. Materials issues related to
Deeper insight into materials degradation mechanisms and data mining

→ Materials Informatics II: Data mining

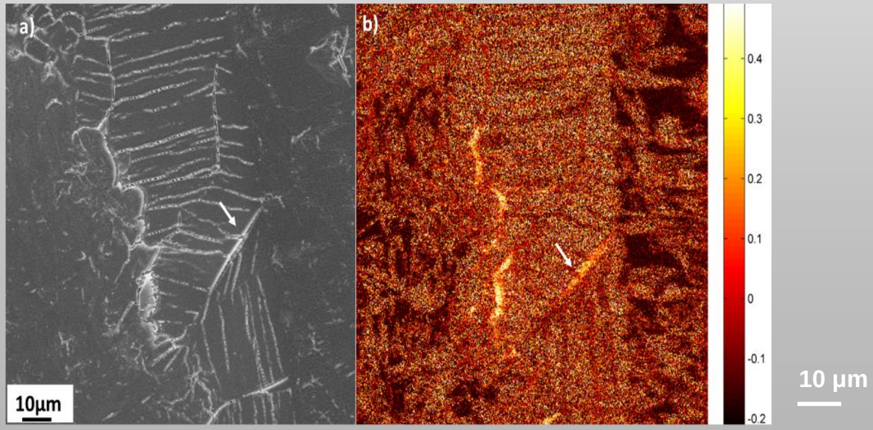
– How can we quantify the various mechanisms to reveal reliable data and threshold values for engineering life time assessment approaches ?

– Do new material properties emerge at extreme conditions and how to quantify them ?

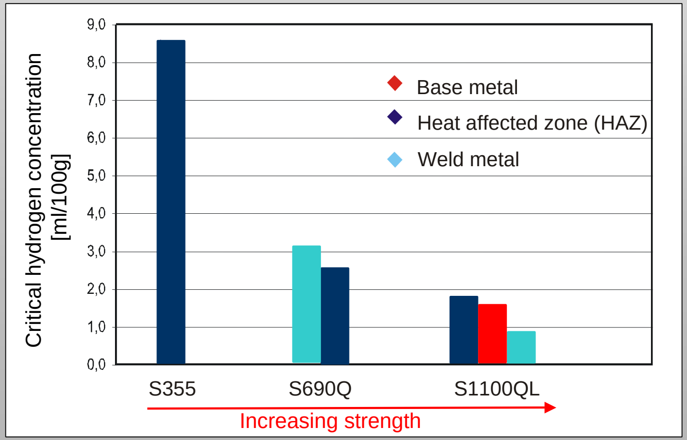
– Can we develop sufficient digital data fusion concepts for multiple analyses and imaging procedures ?

– How can we identify and quantify materials parameters and threshold values for coupled loading and for the large variety of weld and braze filler materials ?

– Can we establish and manage a common (and perhaps freely accessible) platform for materials data and can we validate freely available data for common use ?



High-resolution scanning electron microscopy and ToF-SIMS: Cracking and deuterium distribution in the austenite phase of duplex stainless steels (BAM)



Critical hydrogen concentration for total loss of ductility in common structural steel weld microstructures (BAM)

10 Major Trends
in Materials Science and Technology

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ISMA Innovative Structural Materials Association