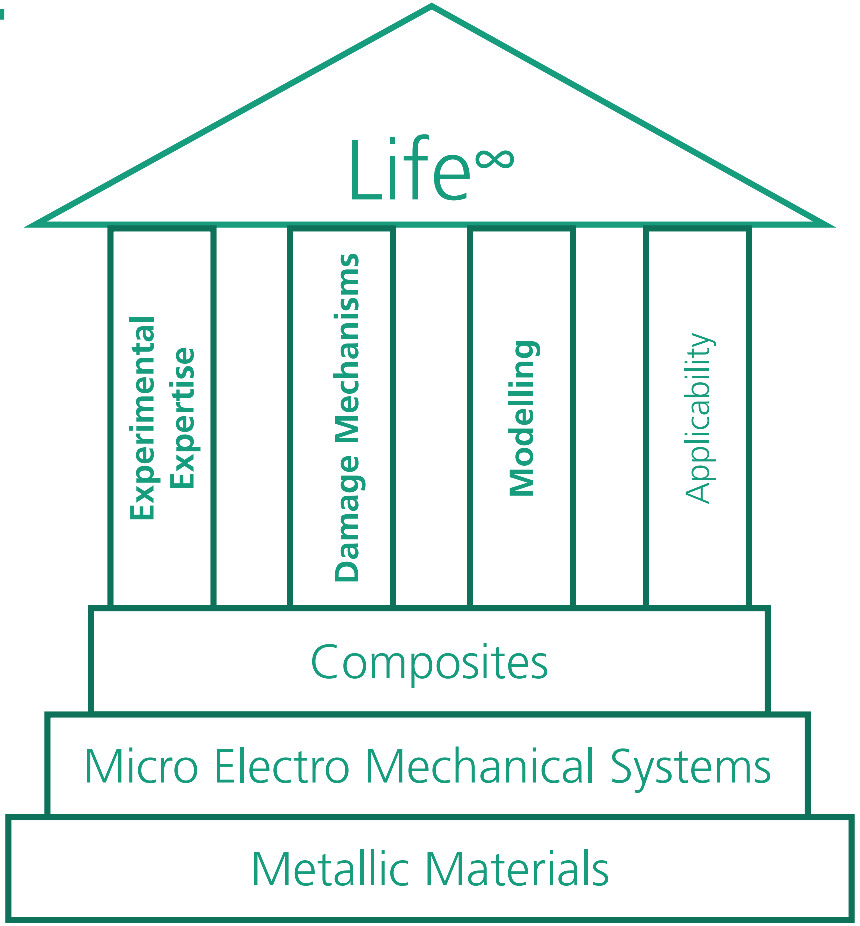
Time shortened fatigue testing for identifying critical process parameters – benefits and limitations

M. Zimmermann, S. Schettler

60 Years RUMUL Symposium

Diessenhofen / Switzerland

My „Lovestory“ with Rumul



Duration 2010 – 2016 (2019)

- 16 projects were funded (including a total of 25 participants)
- Steel: 8 projects,
- Non-ferrous metals: 2 project,
- MEMS: 1 project,
- Composites: 4 projects,
- Coordination: 1 project

My „Lovestory“ with Rumul

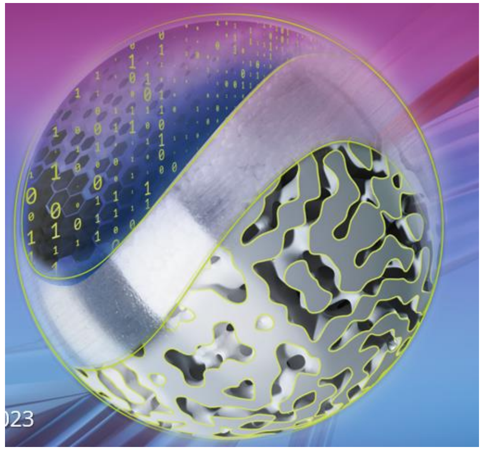
- 1. Testronic Siegen
- 2. Testronic Dresden
- 50 Years Rumul
- 1. Gigaforte Dresden
- 2. Gigaforte Dresden
- 60 Years Rumul

2004

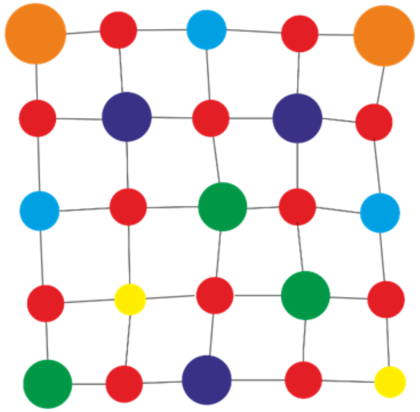
2014

2024

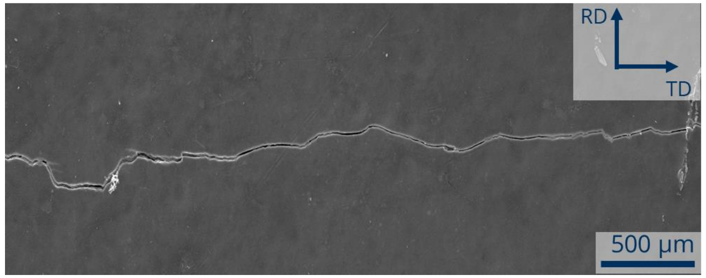
Activities at TU Dresden



Data-driven design
of metamaterials



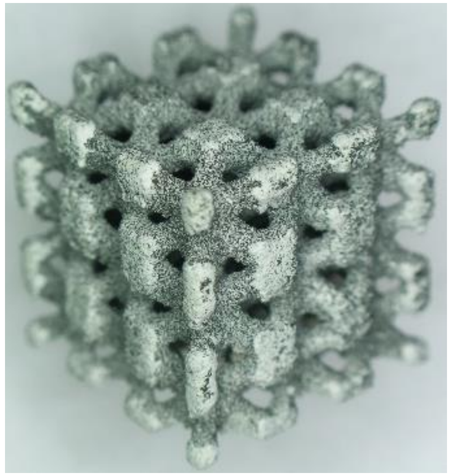
Coatings based on
High Entropy Alloys



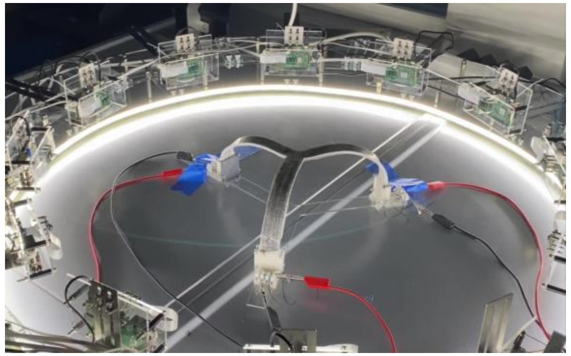
Fatigue Crack Growth in
Mg-Alloys

financed by

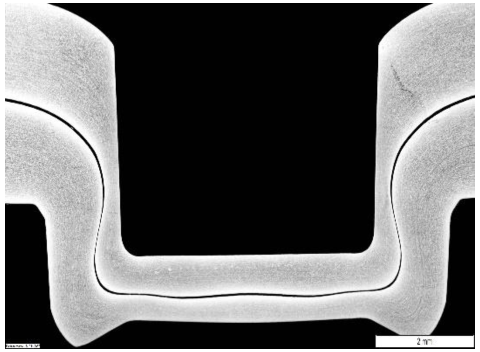
DFG Deutsche Forschungsgemeinschaft



Triply Periodic Minimal
Surface Structures



Interactive fibre elastomers

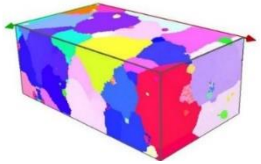


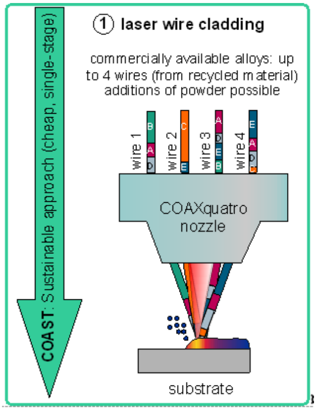
Fatigue of clinched joints

Materials characterization and testing

- Key competences and goals

Thermo-Calc



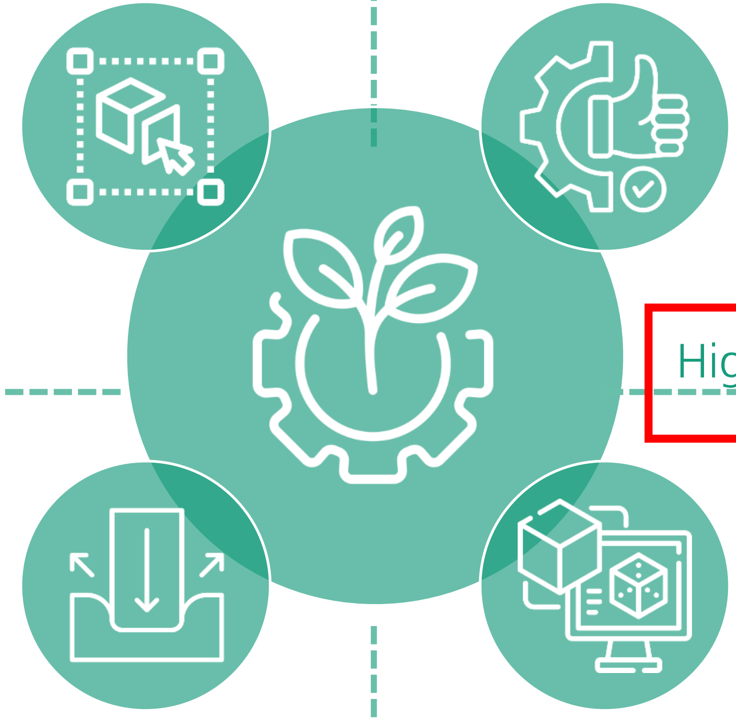


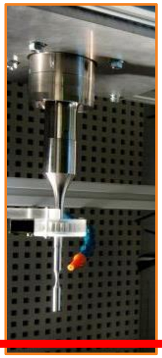
Alloy Design

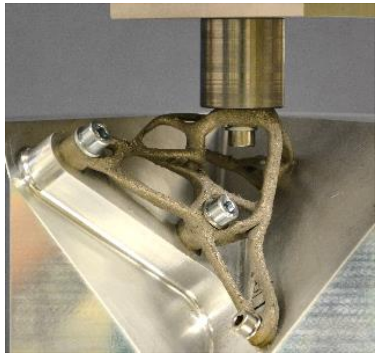
„New" materials: wood

Material Design

Material Reliability





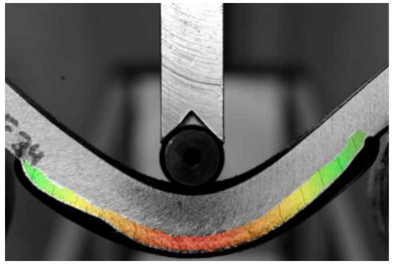


High Frequency Fatigue

3-D-Reconstruction

Implants

Coatings



In-situ deformation

Digitalization

Digitalization of the laboratory

Materials Testing

Equipment: High Frequency Fatigue Testing

Ultrasonic Fatigue Test Equipment

$F_{max} < R_e$

f ≈ 20 kHz

1000Hz - resonance pulsation test bench

$F_{max} = 50$ kN

f ≈ 1000 Hz

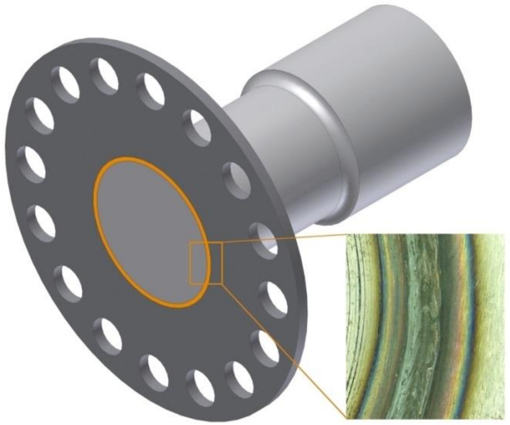
resonance pulsation test bench

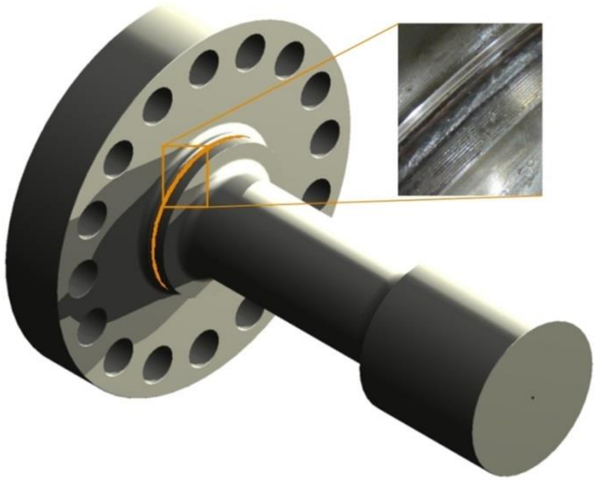
$F_{max} = 100$ kN

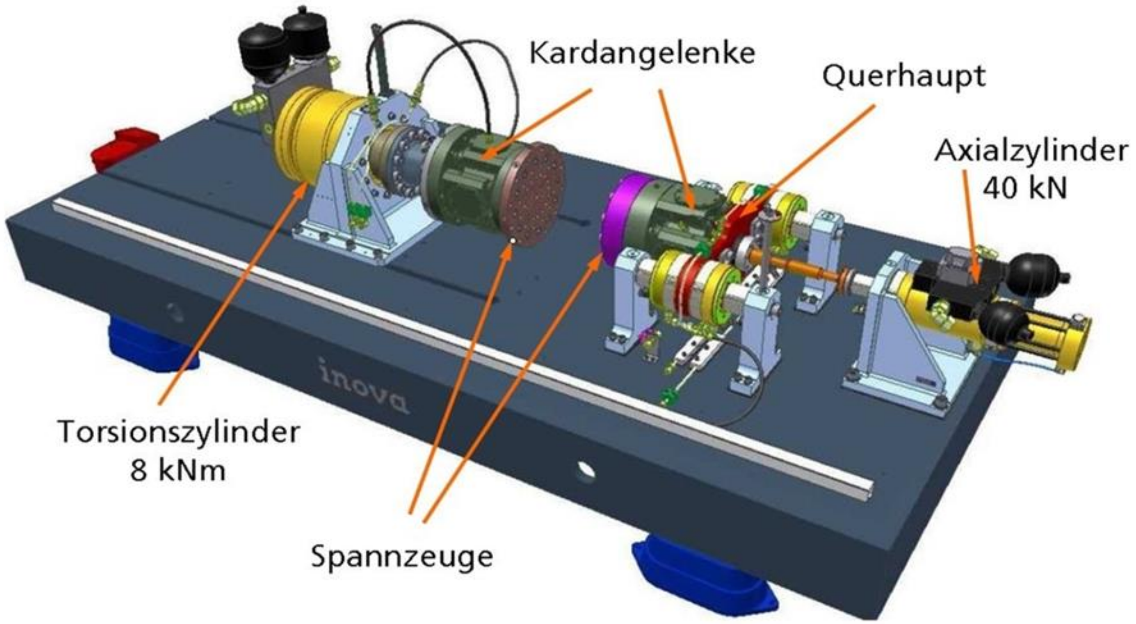
f ≈ 50 - 200 Hz

Materials Testing

Equipment: Multi-axial Testing

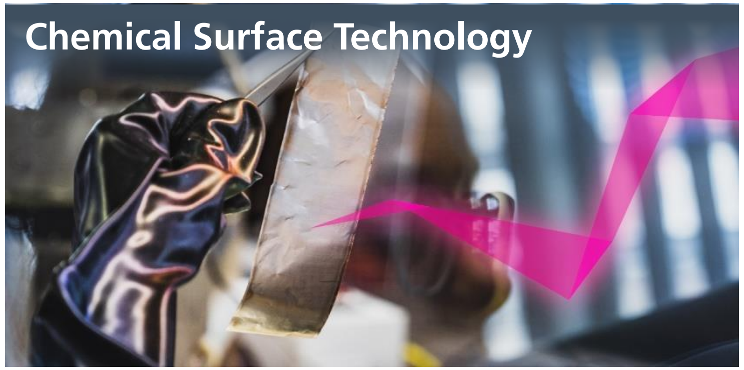






Fraunhofer IWS TECHNISCHE UNIVERSITÄT DRESDEN DRESDEN concept

Activities at Fraunhofer IWS



Any process influences the material condition and hence the fatigue behavior!

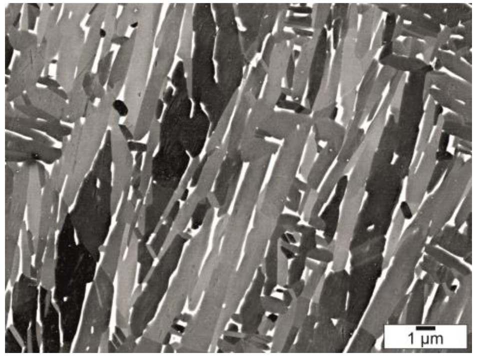
Notch effect

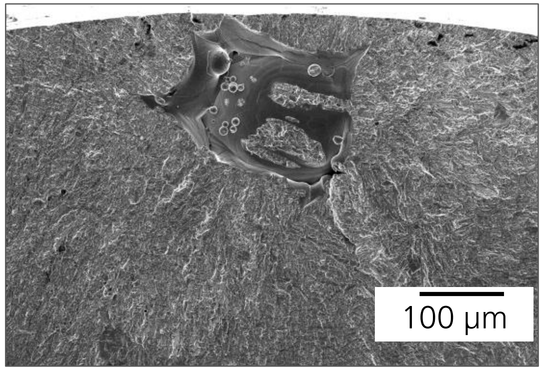
microscopic

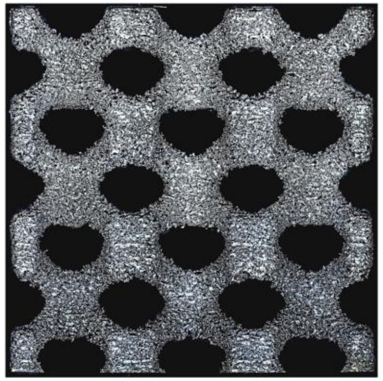
mesoscopic

macroscopic

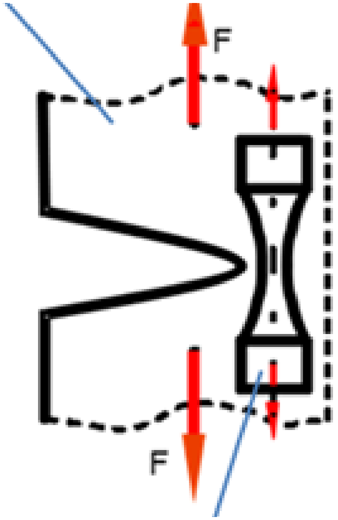
structure / component







2000 µm



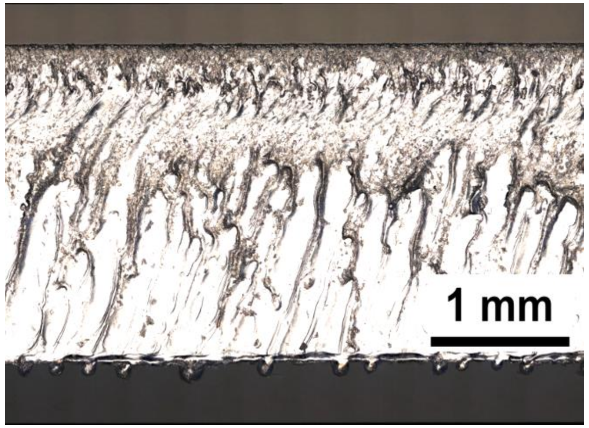
representative material sample

My sincere belief: A reliable fatigue prediction needs an understanding of the underlying damage mechanisms and accompanying statistical evaluations!

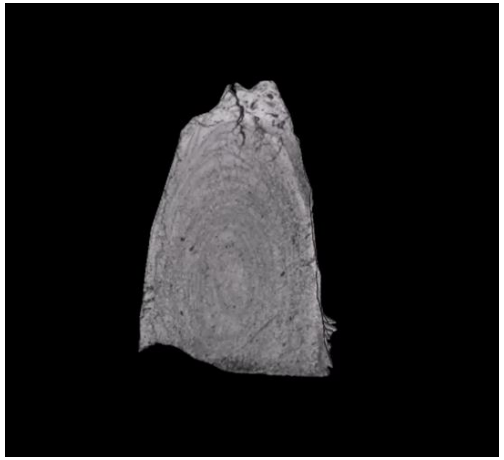
Fraunhofer IWS TECHNISCHE UNIVERSITÄT DRESDEN DRESDEN concept

Laser assisted processing

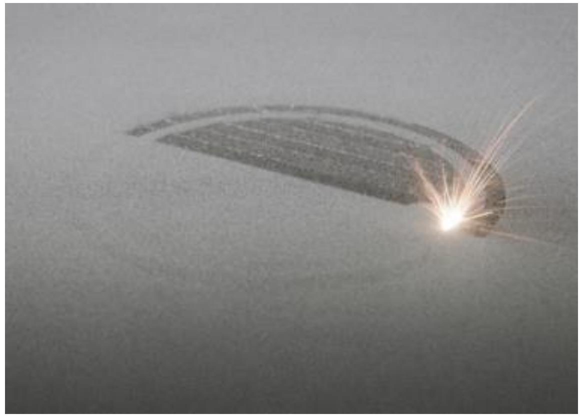
Cutting



Welding

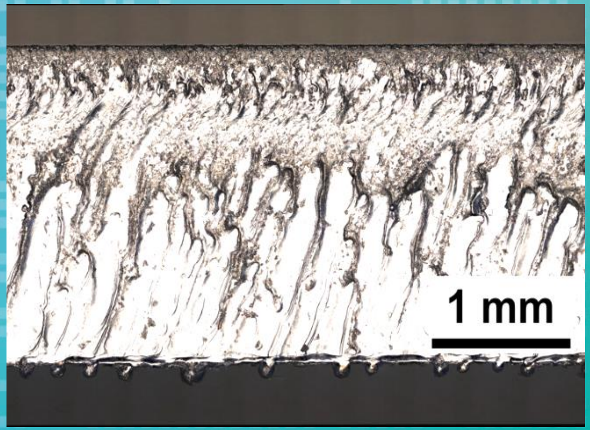


Additive Manufacturing

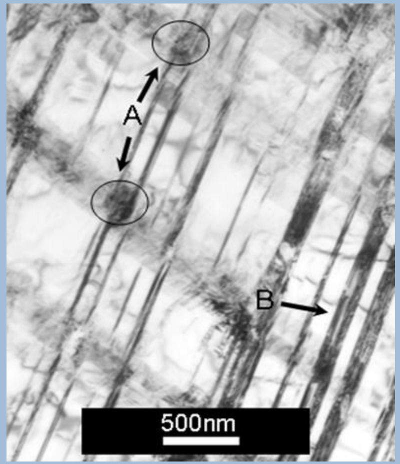


02

Influence of Laser Cutting

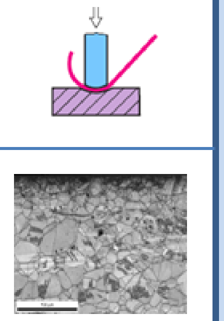


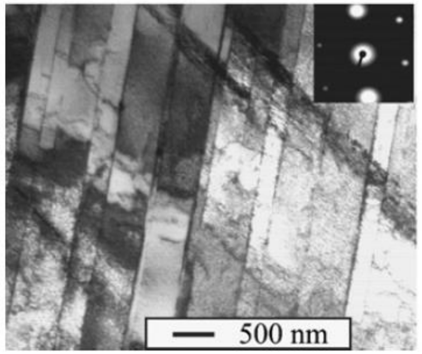
Process-related material condition: forming process



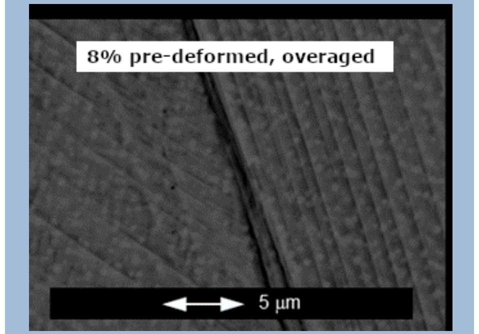
phase transformation

Forming
e.g. bending





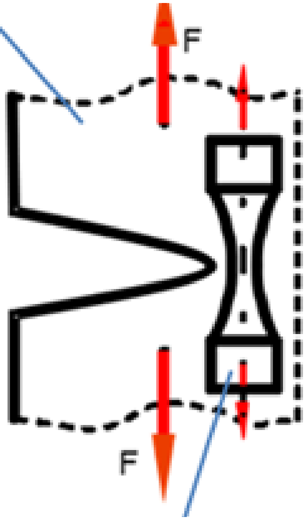
increase in dislocation density



surface roughening

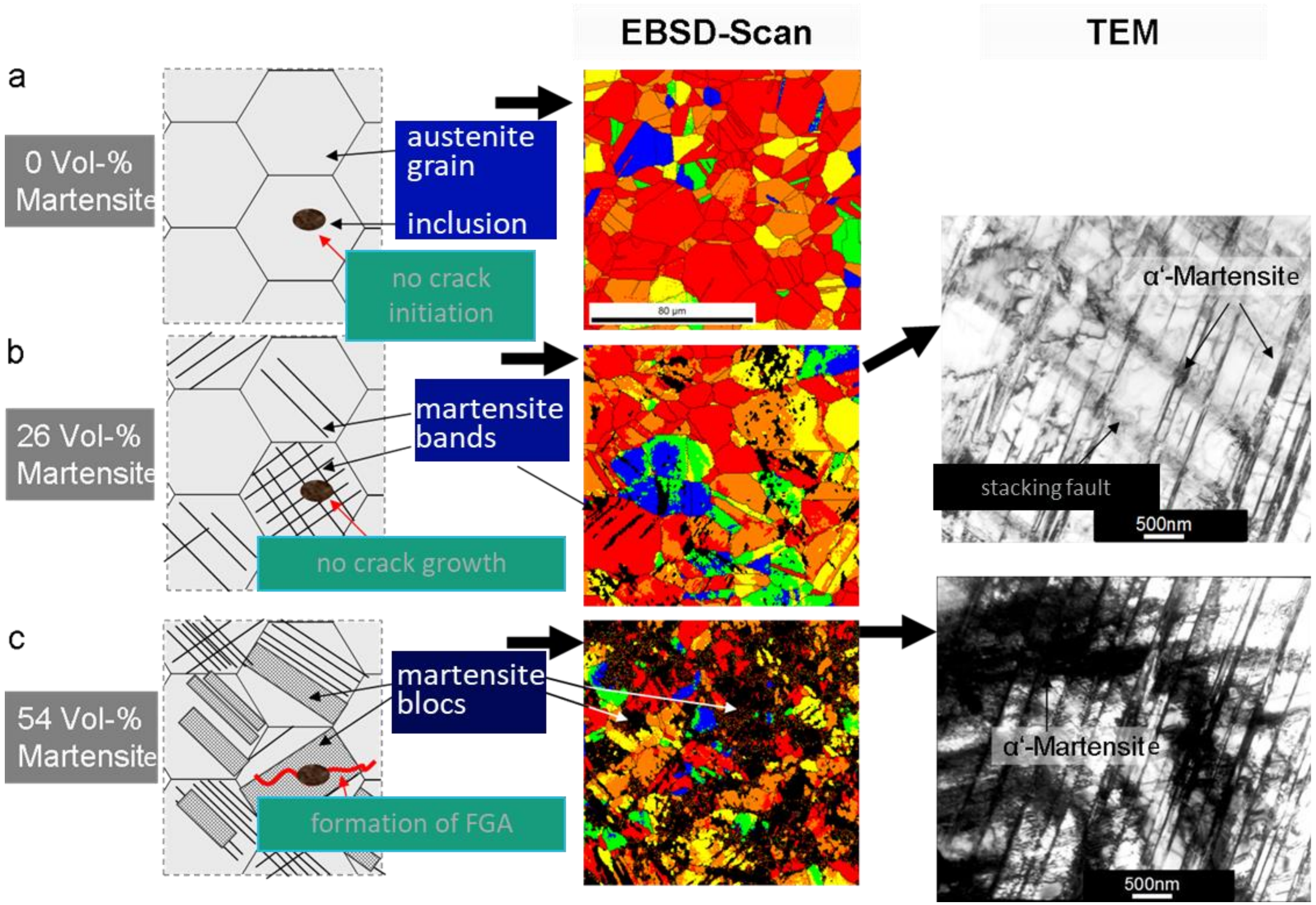
texture

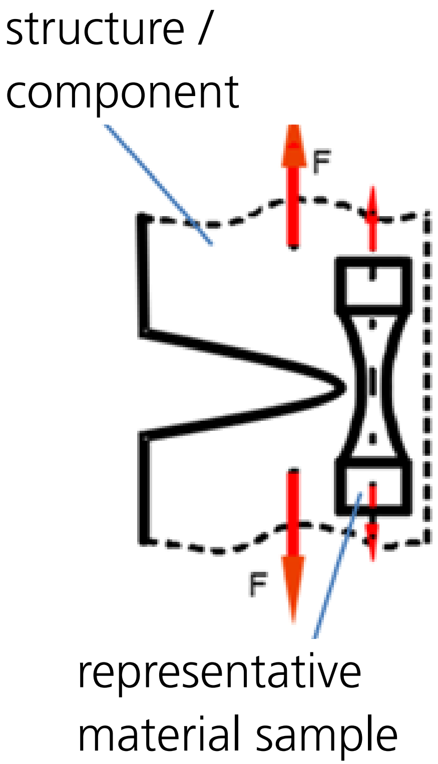
structure / component



representative material sample

Process-related material condition: forming process





Process-related material condition: forming and cutting process

Contents lists available at ScienceDirect
International Journal of Fatigue
journal homepage: www.elsevier.com/locate/ijfatigue

Very high cycle fatigue behaviour of austenitic stainless steel and the effect of strain-induced martensite

C. Müller-Bollenhagen [*], M. Zimmermann, H.-J. Christ
Institut für Werkstofftechnik, Universität Siegen, 57068 Siegen, Germany

Contents lists available at ScienceDirect
International Journal of Fatigue
journal homepage: www.elsevier.com/locate/ijfatigue

Cyclic deformation behavior of austenitic Cr–Ni-steels in the VHCF regime: Part I – Experimental study

CrossMark

A.C. Grigorescu [a,*], P.-M. Hilgendorff [b], M. Zimmermann [c], C.-P. Fritzen [b], H.-J. Christ [a]
[a] *Institut für Werkstofftechnik, Universität Siegen, Siegen 57068, Germany*
[b] *Institut für Mechanik und Regelungstechnik – Mechatronik, Universität Siegen, Siegen 57068, Germany*
[c] *Institut für Werkstoffwissenschaft, Technische Universität Dresden, 01062 Dresden, Germany*

Contents lists available at ScienceDirect
International Journal of Fatigue
journal homepage: www.elsevier.com/locate/ijfatigue

Investigation of the influence of a two-step process chain consisting of laser cutting and subsequent forming on the fatigue behavior of AISI 304

Check for updates

Thomas Wanski [a,*], André T. Zeuner [a], Sebastian Schöne [a], Patrick Herwig [b], Achim Mahrle [b], Andreas Wetzig [b], Martina Zimmermann [a,b]
[a] *Chair of Mechanics of Materials and Failure Analysis, Technische Universität Dresden, Dresden 01069, Germany*
[b] *Fraunhofer Institute for Material and Beam Technology IWS, Dresden 01277, Germany*

Contents lists available at ScienceDirect
Engineering Fracture Mechanics
journal homepage: www.elsevier.com/locate/engfracmech

Influence of surface condition due to laser beam cutting on the fatigue behavior of metastable austenitic stainless steel AISI 304

CrossMark

D.F. Pessoa [a,b,*], P. Herwig [b], A. Wetzig [b], M. Zimmermann [a,b]
[a] *Institut für Werkstoffwissenschaft, Technische Universität Dresden, 01069 Dresden, Germany*
[b] *Fraunhofer-Institut für Werkstoff -und Strahltechnik IWS, 01277 Dresden, Germany*

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International Journal of Fatigue
journal homepage: www.elsevier.com/locate/ijfatigue

Cyclic deformation behavior of austenitic Cr–Ni-steels in the VHCF regime: Part II – Microstructure-sensitive simulation

CrossMark

Philipp-Malte Hilgendorff [a,*], Andrei Cristian Grigorescu [b], Martina Zimmermann [c], Claus-Peter Fritzen [a], Hans-Jürgen Christ [b]
[a] *Institut für Mechanik und Regelungstechnik – Mechatronik, Universität Siegen, Siegen 57068, Germany*
[b] *Institut für Werkstofftechnik, Universität Siegen, Siegen 57068, Germany*
[c] *Institut für Werkstoffwissenschaft, Technische Universität Dresden, Dresden 01062, Germany*

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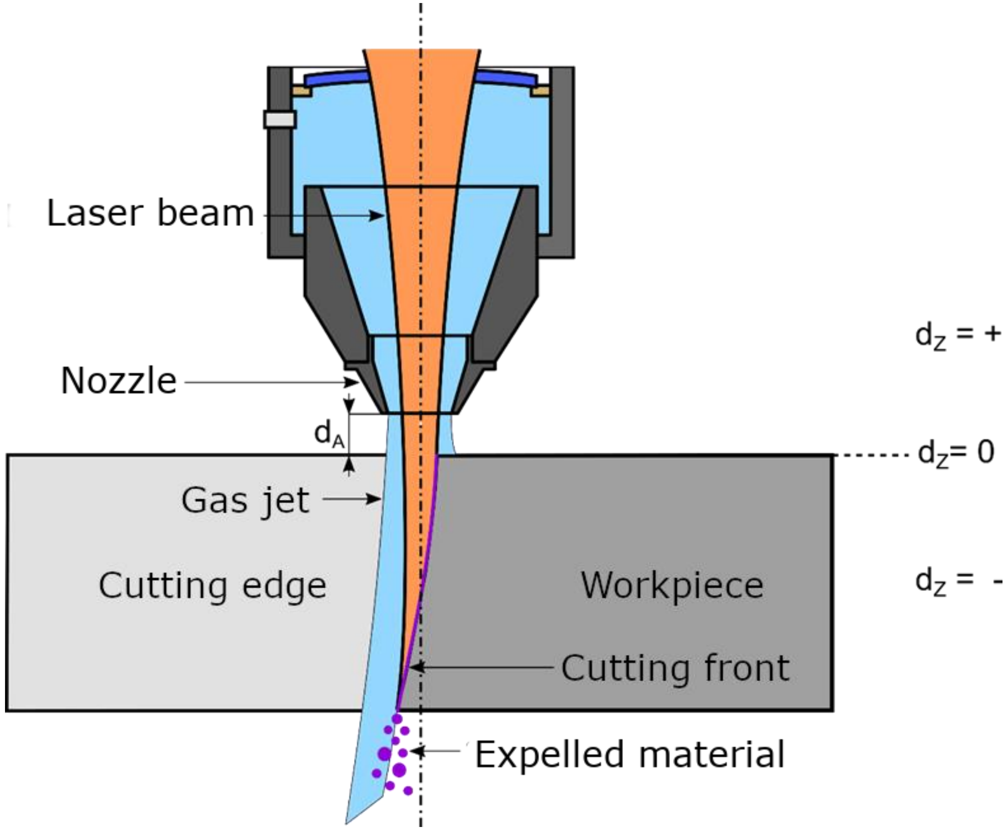
DRESDEN concept

Laser cutting

- The focused laser beam hits the workpiece and melts the material locally
- A gas jet coaxial with the laser beam expells the material

- <u>Process parameters for cutting:</u>
  - – Laser power P_L
  - – Gas pressure p_{gas}
  - – Feed rate v
  - – Focal position d_Z
  - – Working distance d_A
  - – Nozzle diameter d_d



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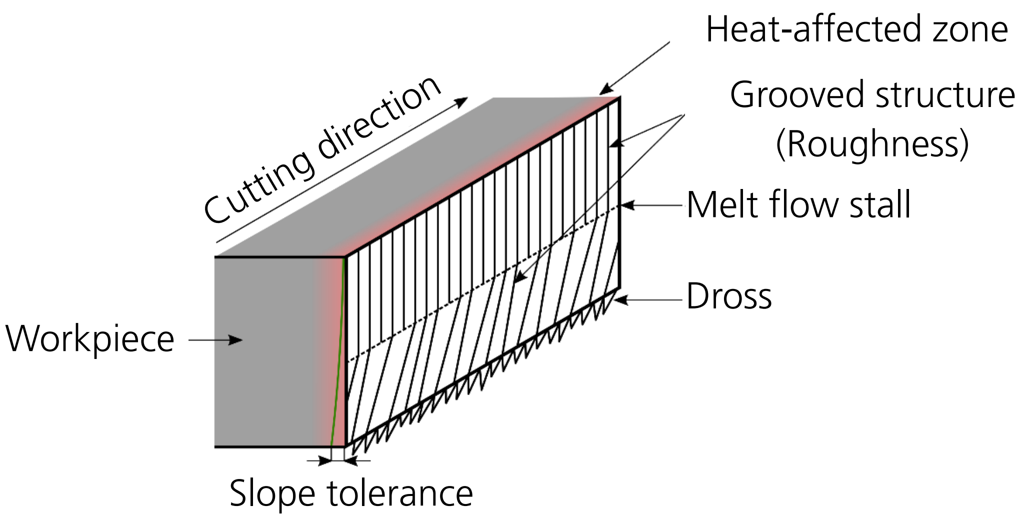
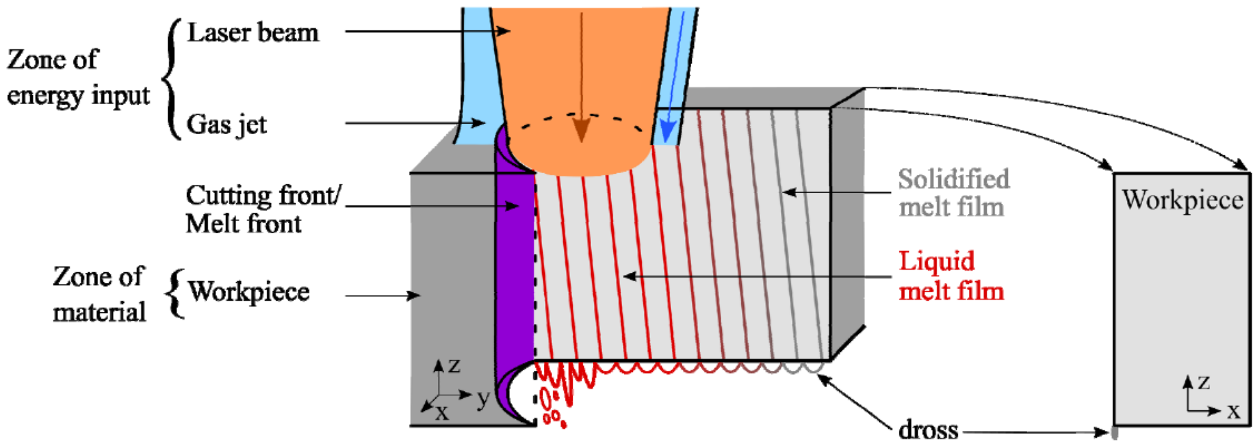
DRESDEN concept

Laser cutting
Cutting edge phenomena

Cutting edge phenomena:

- Grooved structure (Roughness)
- Heat-affected zone
- Slope tolerance
- Melt flow stall
- Dross adhesion





The dross is created from the melt film
→ Influenced by the process parameters

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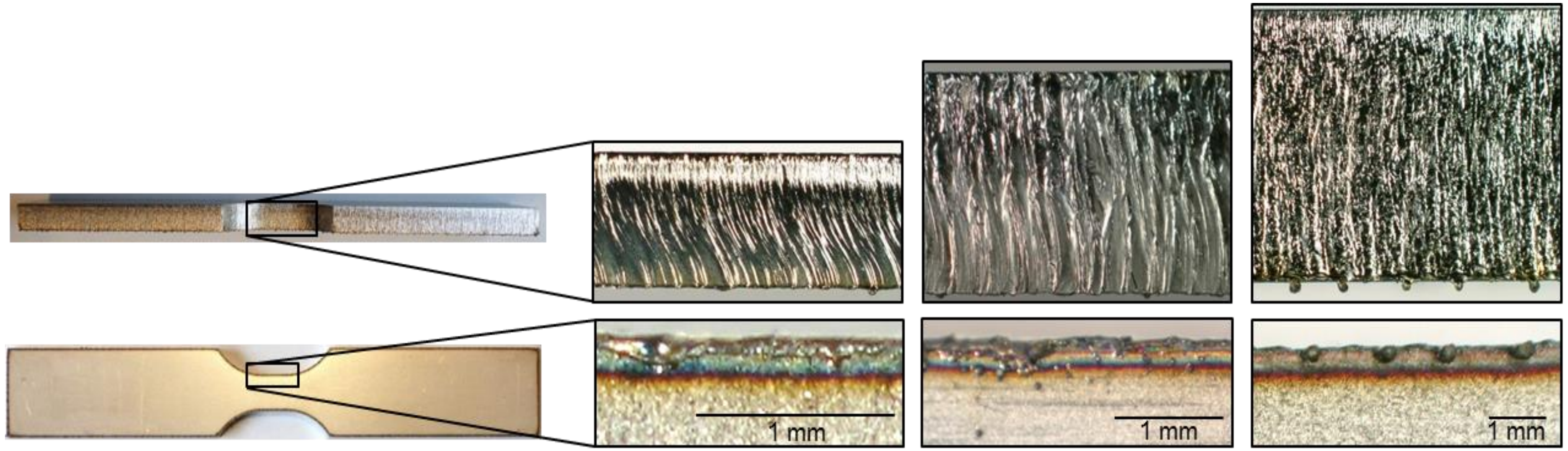
DRESDEN concept

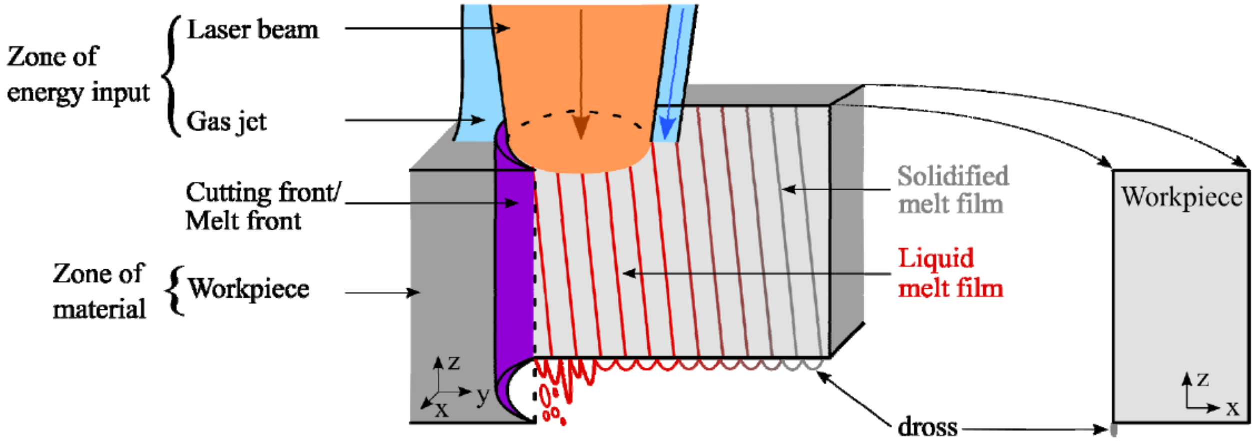
Laser cutting

Cutting edge phenomena



<u>Cutting edge phenomena:</u>

- Grooved structure (Roughness)
- Heat-affected zone
- Slope tolerance
- Melt flow stall
- dross adhesion



The dross is created from the melt film
→ Influenced by the process parameters

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DRESDEN concept

Laser cutting
Representative dross shapes

a) Dross-free

b) Small droplets

c) Large droplets

d) Very coarse dross

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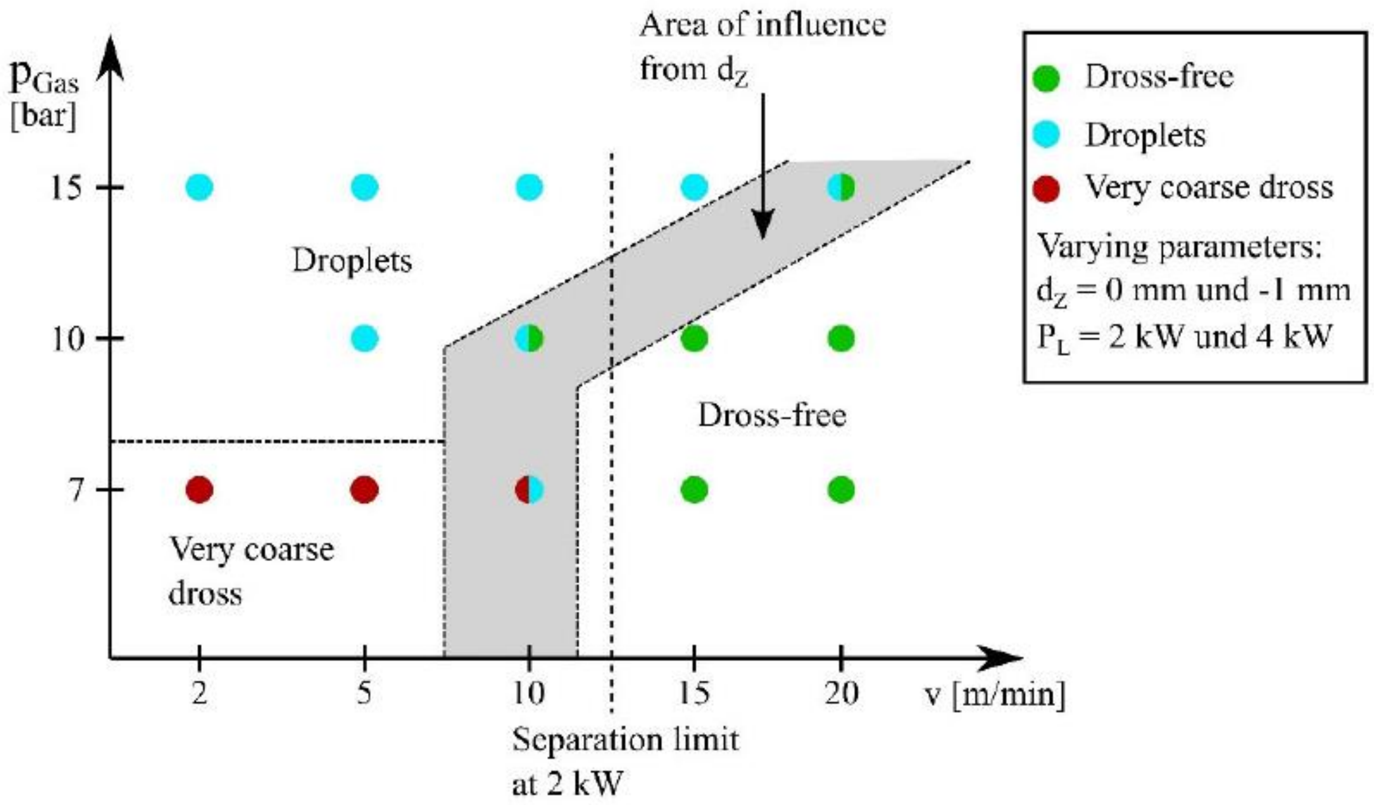
DRESDEN concept

Laser cutting
Influences on dross shapes

- Feed rate v
- Gas pressure p_{Gas}
- Focal position d_Z
- Laser power P_L



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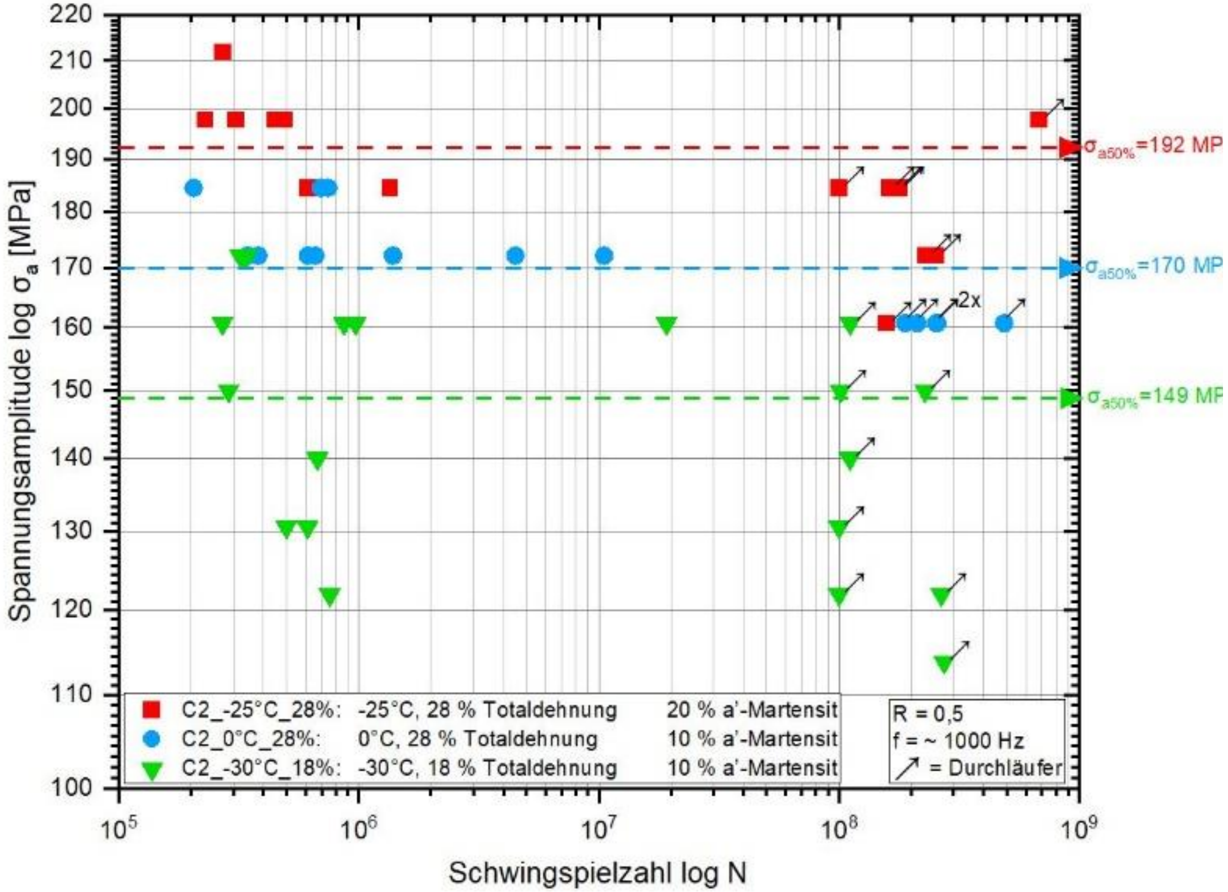
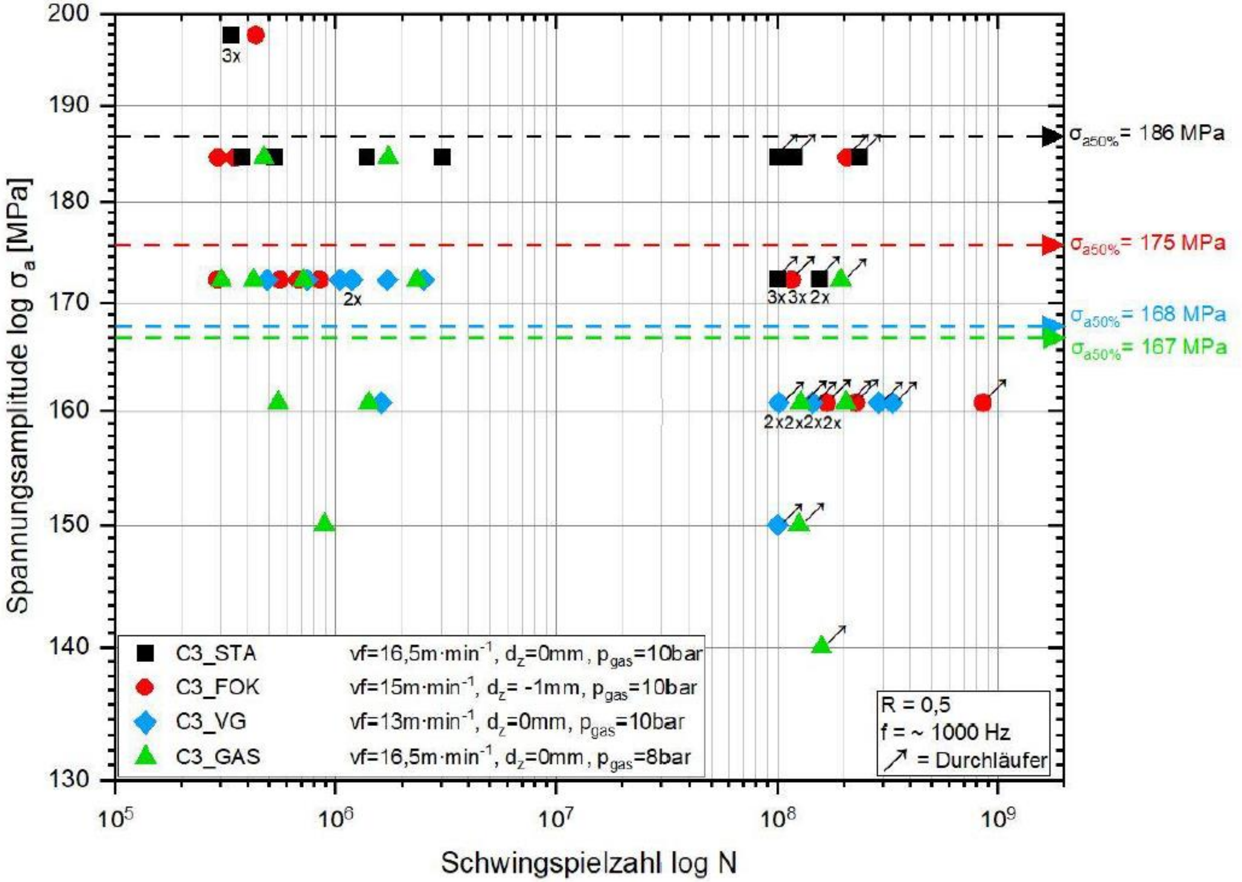
Laser cutting

Fatigue behavior depending on the material condition AND the process parameters





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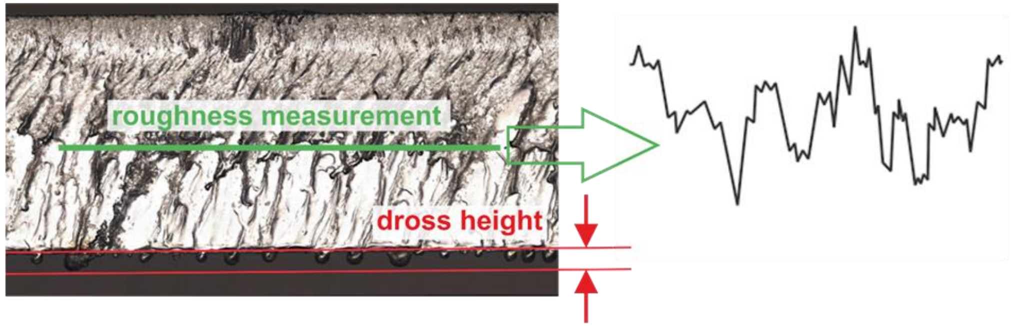
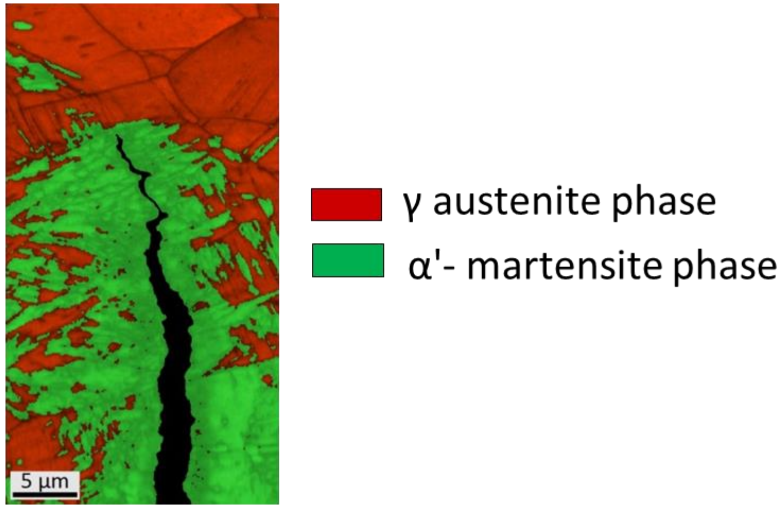
Laser cutting

Material: 1.4301 – metastable austenitic steel

VHCF behavior of laser-cut 1.4301

- deformation-induced α' martensite volume fraction
- strain-hardening due to pre-deformation
- notch effects (melt droplets)
- localized martensite formation in the notch root (melt droplets)
- detachment of droplets due to degree of pre-deformation





--> dominating notch effect: mesoscopic, however microstructural effect (phase transformation) results in true durability in the VHCF regime

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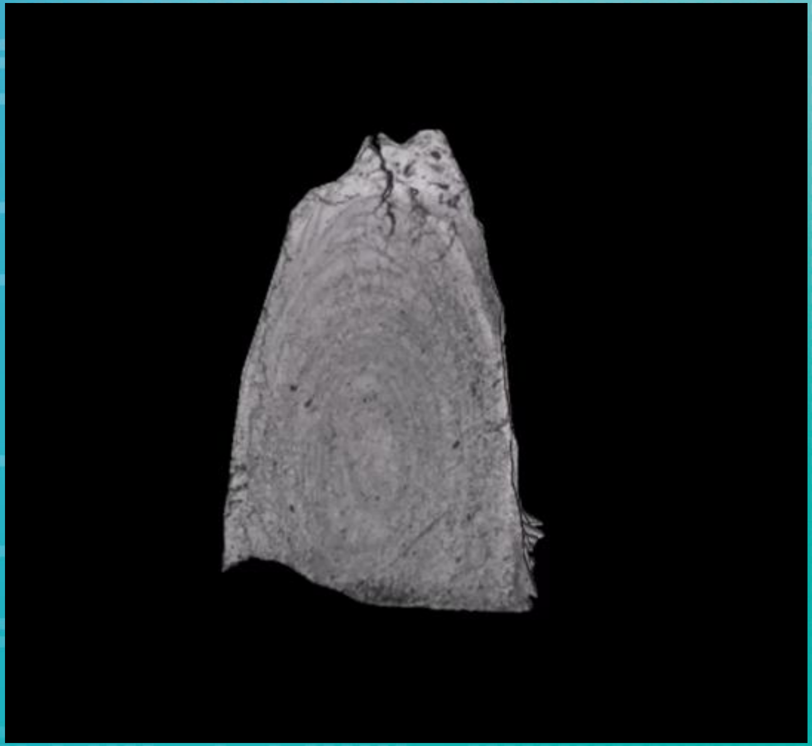
03

Influence of laser beam welding



Process-related material condition: joining process

Contents lists available at SciVerse ScienceDirect
International Journal of Fatigue
journal homepage: www.elsevier.com/locate/ijfatigue

High-frequency cyclic testing of welded aluminium alloy joints in the region of very high cycle fatigue (VHCF)

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Institut für Werkstofftechnik, Universität Siegen, 57068 Siegen, Germany

Contents lists available at ScienceDirect
Journal of Advanced Joining Processes
journal homepage: www.sciencedirect.com/journal/journal-of-advanced-joining-processes

Effect of the tool geometry on microstructure and geometrical features of clinched aluminum

Lars Ewenz [1,*], Martin Kuczyk [1], Martina Zimmermann [1,2]
[1] Institute of Materials Science, TU Dresden, 01062 Dresden, Germany
[2] Fraunhofer Institute for Material and Beam Technology IWS, 01277 Dresden, Germany

Advanced Materials Research
ISSN: 1662-8985, Vols. 891-892, pp 1397-1402
doi:10.4028/www.scientific.net/AMR.891-892.1397

Online: 2014-03-12

Fatigue behaviour of laser beam welded circular weld seams under multi-axial loading

Martina Zimmermann[1,2,a], Jörg Bretschneider [2,b], Gunter Kirchhoff [2,c], Uwe Stamm [2,d], Jens Standfuss [2,e], Berndt Brenner [2,f]
[1]Institut für Werkstoffwissenschaft, TU Dresden, D-1069 Dresden, Germany
[2]Fraunhofer Institut für Werkstoff- und Strahltechnik, D-01277 Dresden, Germany
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[c]gunter.kirchhoff@ iws.fhg.de, [d]uwe.stamm@ iws.fhg.de, , [e]jens.standfuss@ iws.fhg.de,
[f]berndt.brenner@ iws.fhg.de

metals
MDPI

Article

Fatigue Behavior of Laser-Cut Sheet Metal Parts with Brazed-On Elements

André Till Zeuner [1], Robert Kühne [2,*], Christiane Standke [1], David Köberlin [3], Thomas Wanski [1], Sebastian Schettler [2], Uwe Füssel [3] and Martina Zimmermann [1,2]

VHCF 8: Fatigue behavior of brazed joints

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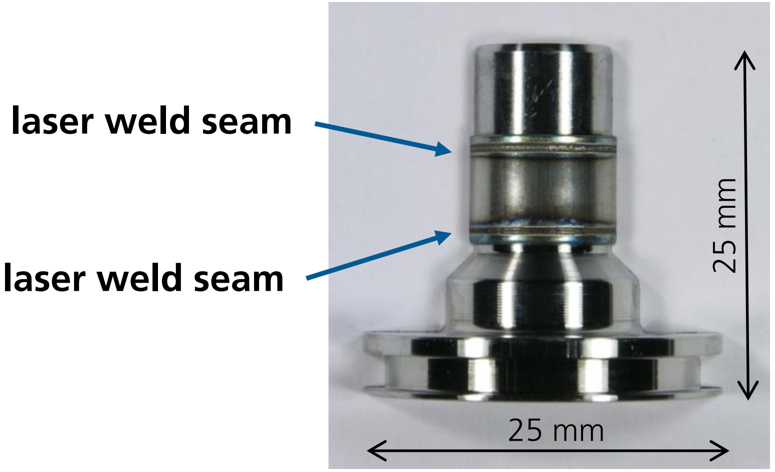
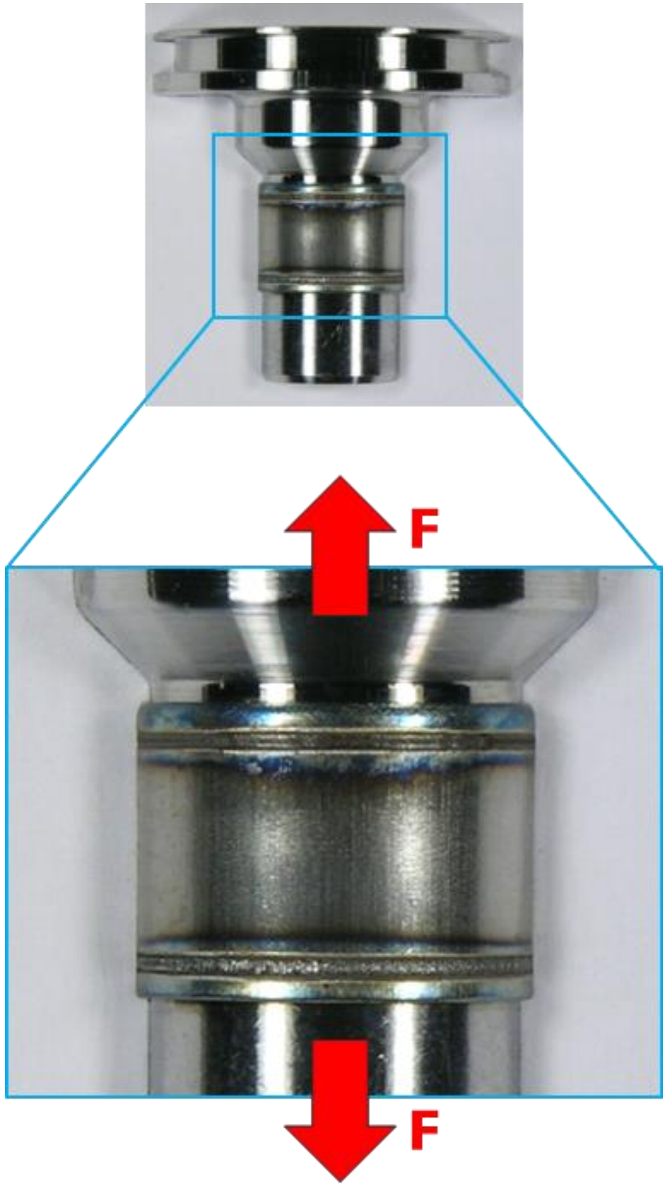
TECHNISCHE UNIVERSITÄT DRESDEN
DRESDEN concept

Laser Beam Welding

joined steel component

- Fatigue Testing up to $\mathbf{N_G = 10^8}$ loading cycles
- Test frequency: approx. **1.000 Hz**
- Test bench: Gigaforte 50 (resonance pulsation test bench)





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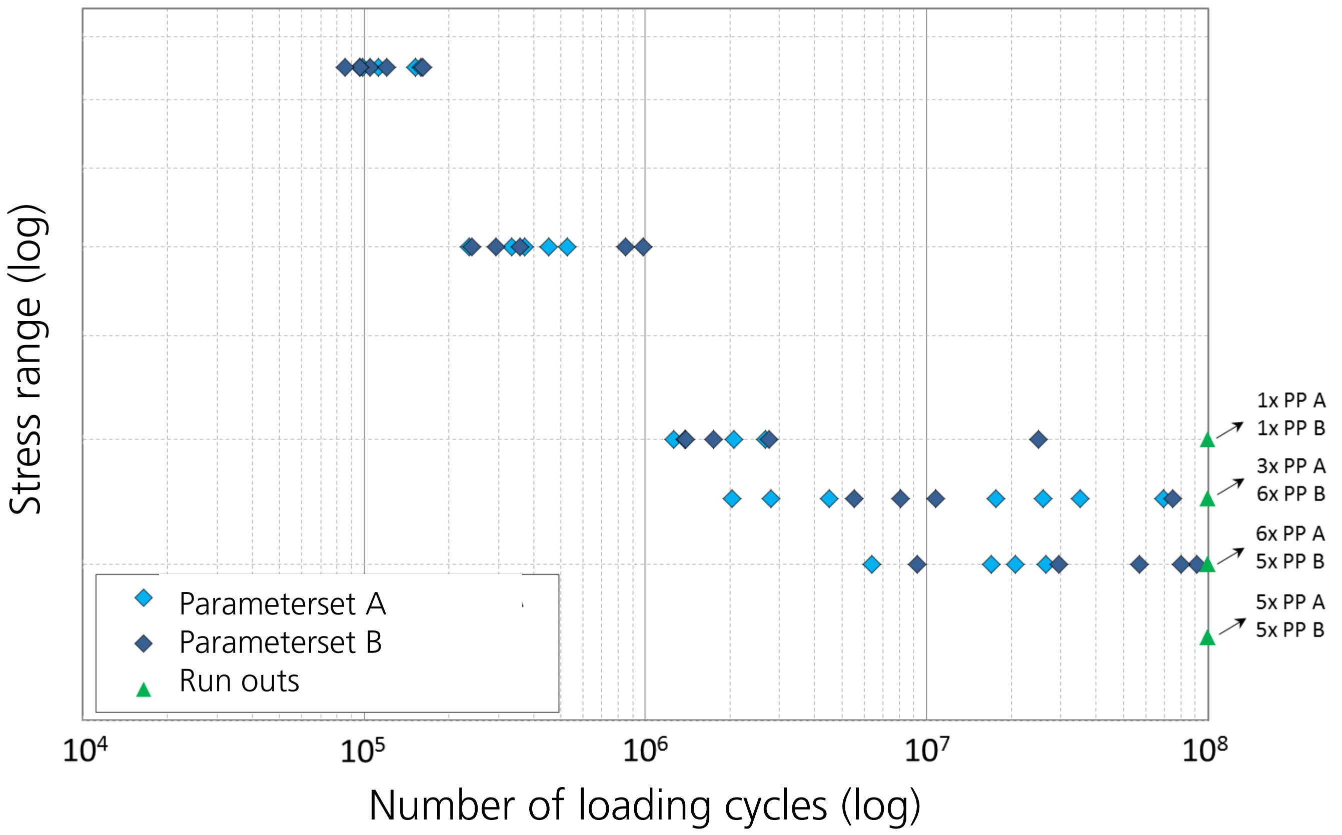
Laser Beam Welding

joined steel component

Σ 60 samples / $N_G = 10^8$ Zyklen

- Parameterset A leads to higher scatter at low loads → higher probability of failure
- Many failures at high numbers of loading cycles (from 10^7 up to 10^8)
- Component failure in VHCF - range!

S – N – diagram: Variation of process parameters



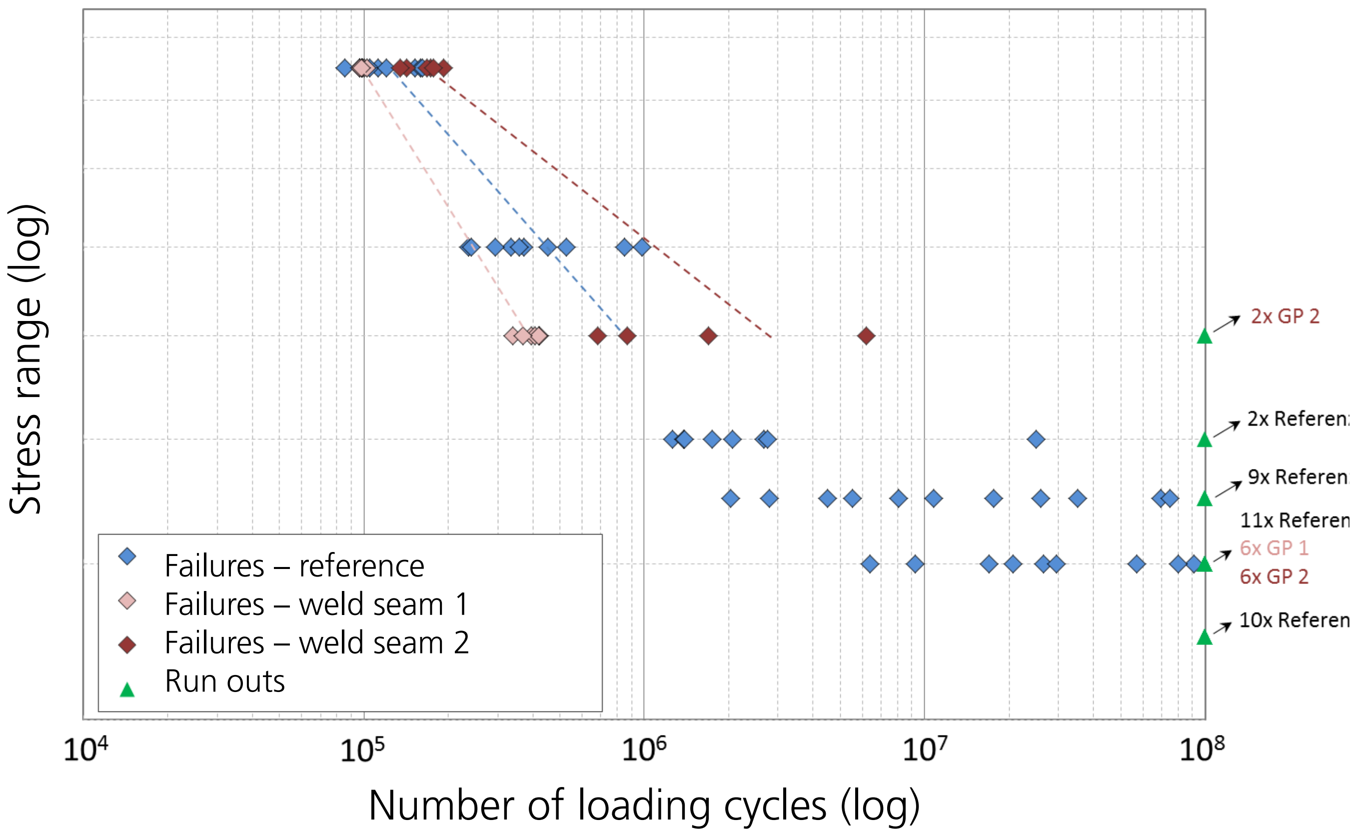
--> dominating notch effect: combination of mesoscopic and macroscopic effect with failure at weld root in the range of the laser entry point

Laser Beam Welding

joined steel component

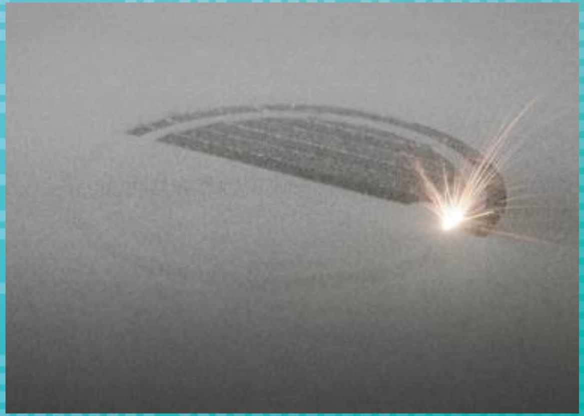
- Significant influence of minor geometrical changes in weld seam!
- unfavorable weld position causes earlier component failures!
- Change of the failure location

S – N – diagram: Variation of geometrical features

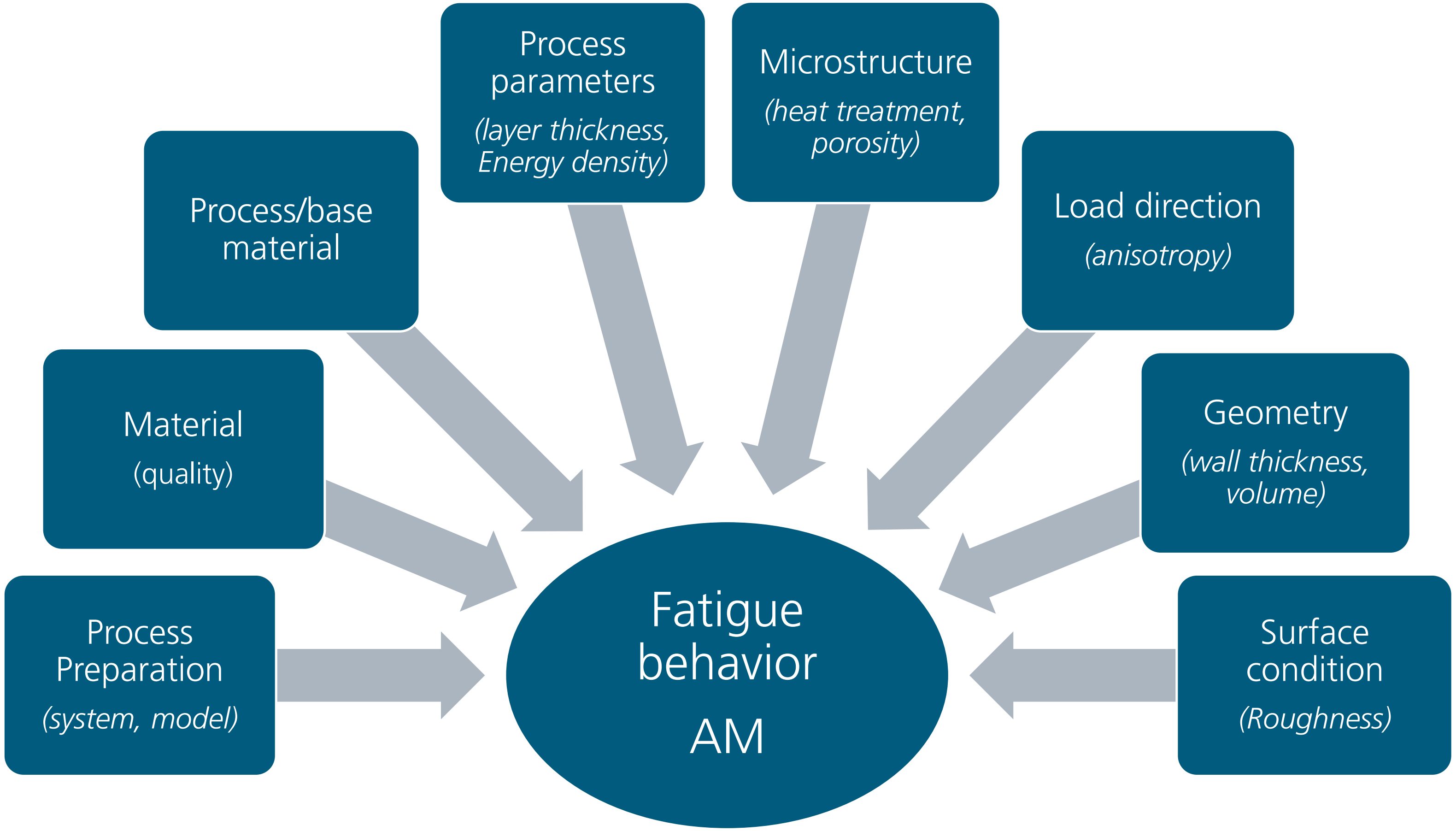


04

Influence of additive manufacturing



Additive Manufacturing

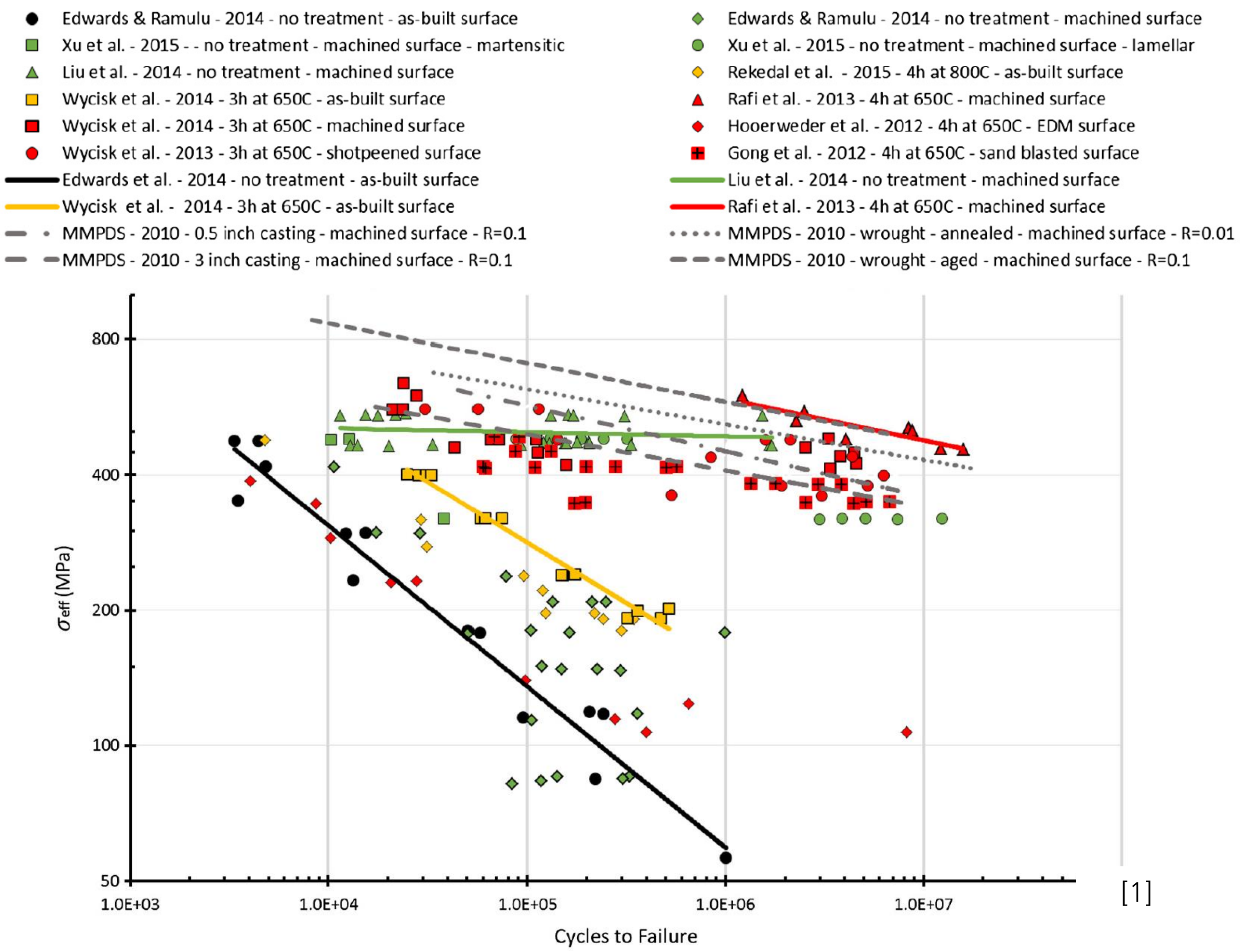


Additive Manufacturing

- large scattering, even of apparently similar conditions

Prediction of fatigue life difficult:

- often incomplete informations about the manufacturing process, material quality and causes of failure



[1]

Quelle: [1] P. Li et al.: *International Journal of Fatigue Volume 85, April 2016, Pages 130-143*

Additive Manufacturing

- Example: Ti6Al4V
- L-PBF – Process
- Variation of
  - L-PBF machine
  - Layer thickness
  - Laser power
  - Scanning speed
  - Orientation
  - Heat treatment

Goals: Process parameters → high density! (consistently > 99,8%)

Heat treatment → application-oriented approach (based on VDI 3405 Sheet 2.4)
→ Reduction of process-related residual stresses

Methods

- Material: Inert gas atomised Ti-6Al-4V Grade 23 (ELI), LPBF process

	Batch 1 (C1)	Batch 2 (C2)	Batch 3 (C3)	Batch 4 (C4)	Batch 5 (C5)	Batch 6 (C6)	Batch 7 (C7)	Batch 8 (C8)
Layer thickness in µm	30		60		25			50
Power in W	200		300		200			370
Scan velocity in mm/s	850		750		1200			1500
Building direction	**0°** (↕)	**90°** (↔)	**0°** (↕)	**90°** (↔)	**0°** (↕)			**0°** (↕)
Heat treatment	SR		SR		SR	HIP	AN	AN

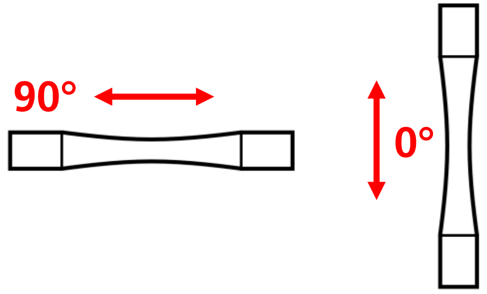
SR … Stress relieved

HIP… Hot Isostatic Pressing

AN … Annealed

→ **A total of 202 specimens manufactured**

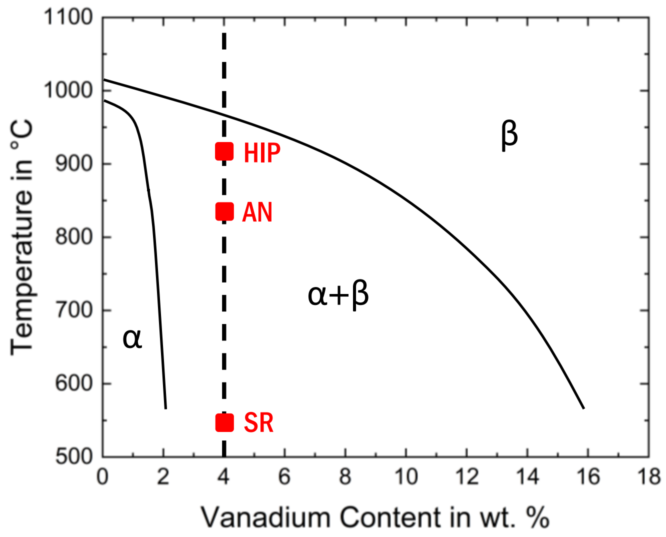
Building direction:



Methods

- Material: Inert gas atomised Ti-6Al-4V Grade 23 (ELI), LPBF process

Heat treatment	Parameter
Stress relieved (SR)	550 °C / 180 min / Argon / furnace cooling
Annealed (AN)	842 °C / 270 min / Argon / furnace cooling to 200°C, cooling to RT using Argon
Hot Isostatic Pressing (HIP)	920 °C / 120 min / 1000 bar



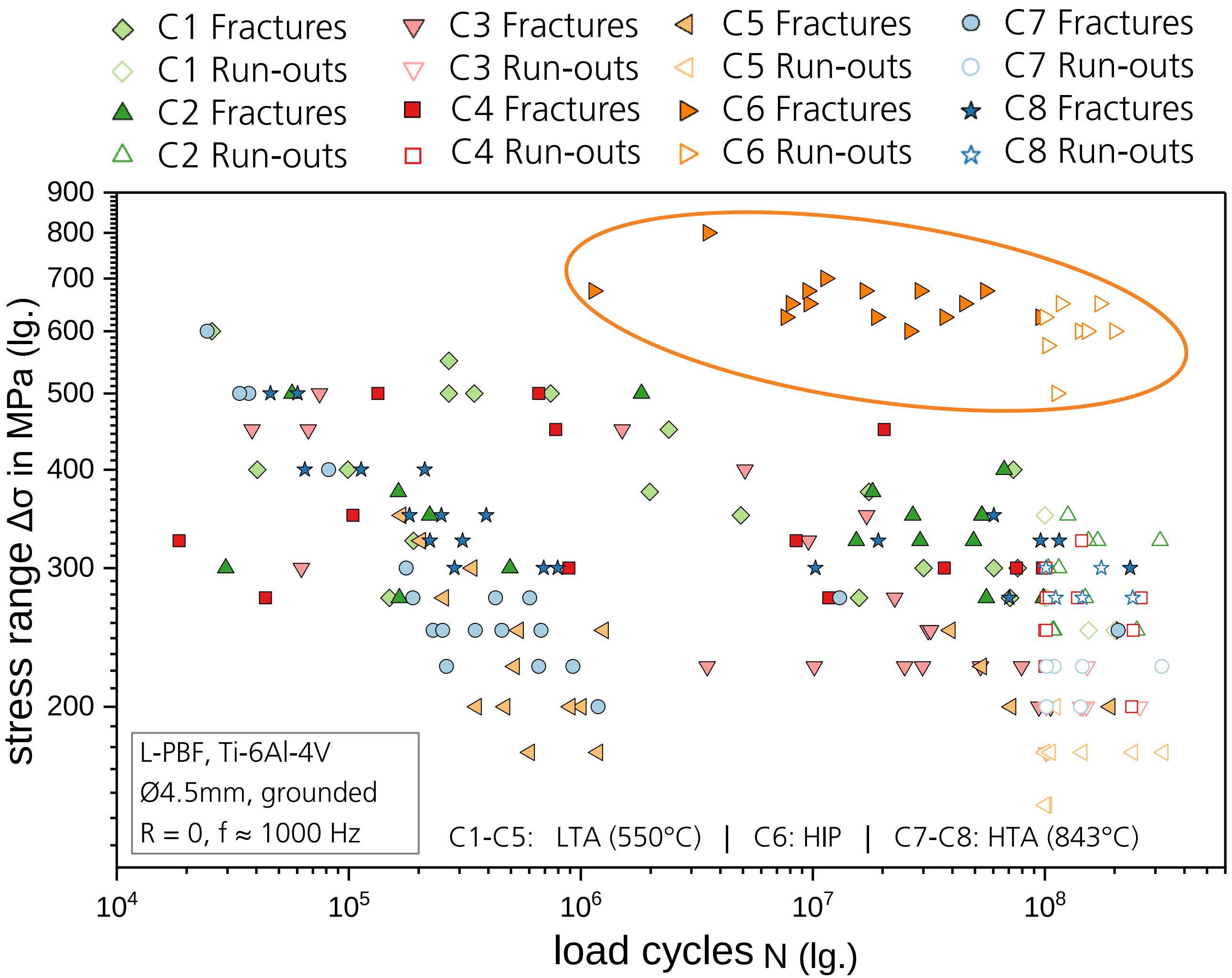
Additive Manufacturing

S-N curve – Overall comparison

- **C6** → HIP-heat treatment leads to significant increase in fatigue strength (factor ≥ 2)
- Large number of failures beyond the knee point (N ≈ 10^6) of the S-N curve
- Scattering over several decades within individual batches

➡ stochastic distribution of the defect population within the batches

➡ Analysis of the S-N curve is subject to great uncertainty



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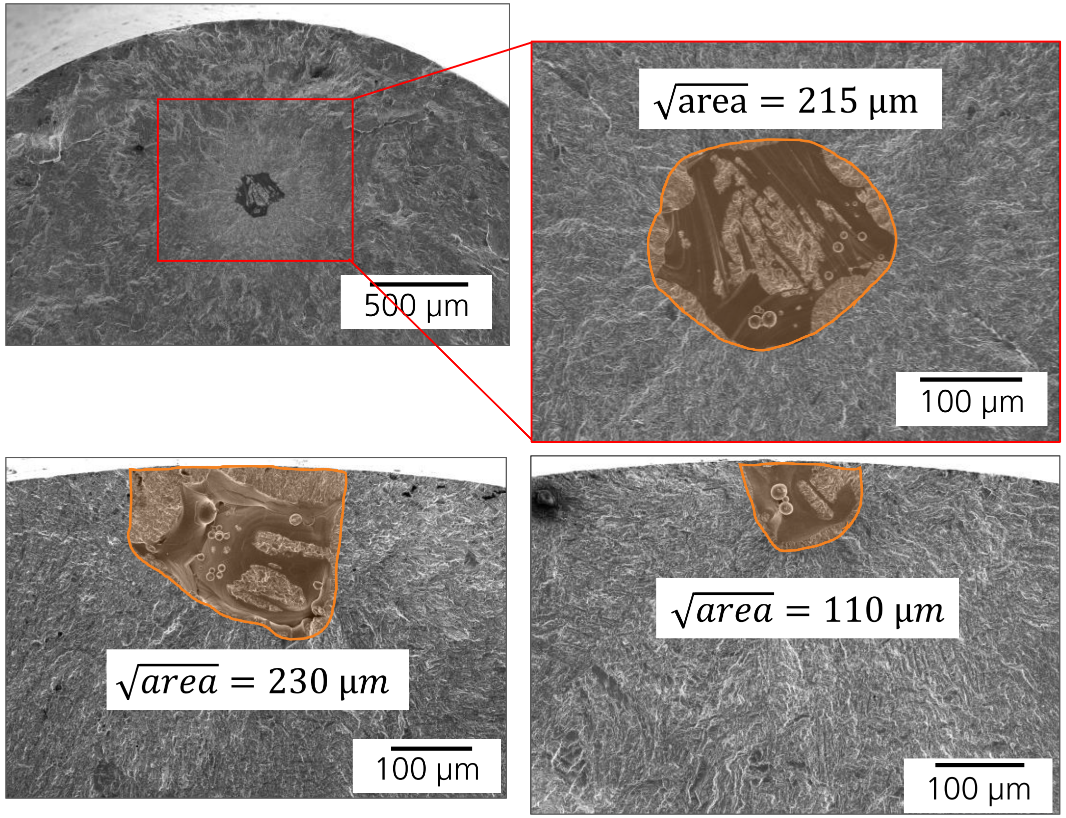
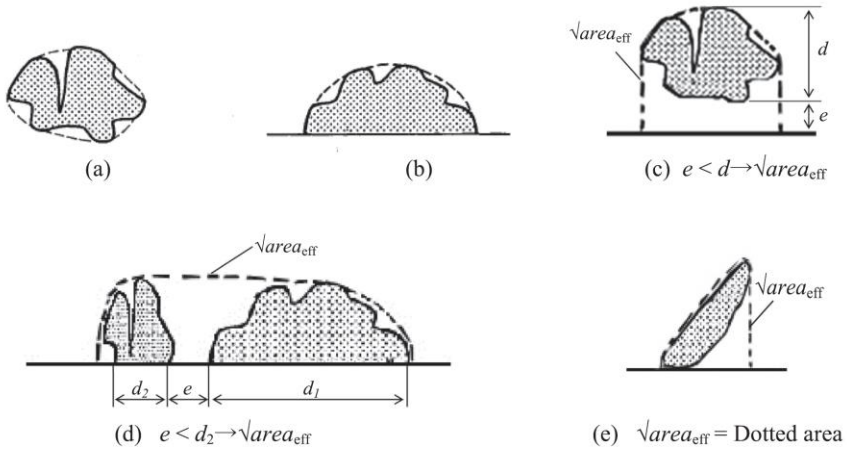
Additive Manufacturing

Evaluation of the failure-causing defects according to the $\sqrt{area}$ - concept





$$\sigma_w = \frac{C(HV + 120)}{(\sqrt{area})^{1/6}}$$

σ_w… Estimated fatigue strength according to Murakami ($\sigma_w = \sigma_a$)

C… Constant (surface defects: 1,43 / volume defects: 1,56)

HV… Microhardness of the material in the direct area of the defect

Source: Murakami, Metal Fatigue: Effects of Small Defects and…, Elsevier, 2002

Application of Kitagawa-Takahashi diagramm

El-Haddad approach

$$\Delta\sigma_{1E8} = \Delta\sigma_{1E8,0}\sqrt{\frac{a_0}{a+a_0}} = \Delta\sigma_{1E8,0}\sqrt{\frac{\sqrt{area_{eff0}}}{\sqrt{area_{eff}}+\sqrt{area_{eff0}}}} \quad \text{with} \quad a_0 = \sqrt{area_{eff0}} = \frac{1}{\pi}\left(\frac{\Delta K_{th,LC}}{C * \Delta\sigma_{1E8,0}}\right)^2$$

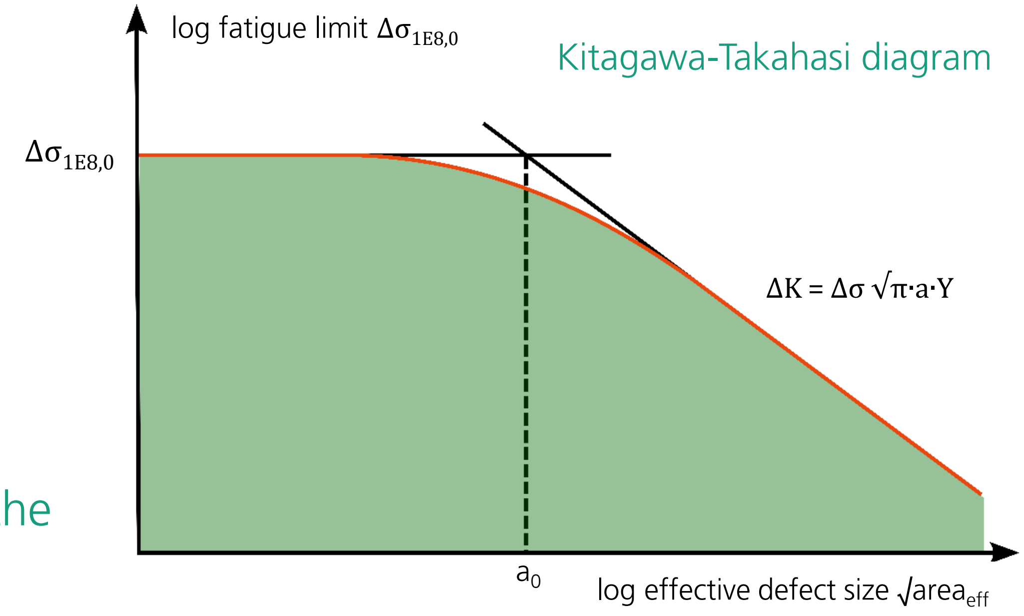
- Estimation of $\Delta\sigma_{1E8,0}$ and $\Delta K_{th,LC}$

$$\Delta\sigma_{1E8,0} = 6{,}4HV\left(\frac{1-R}{3-R}\right)$$

$$\Delta K_{th,LC} = 1{,}82 \cdot l^{0{,}165} + 53{,}5 \cdot \mathrm{HV}^{-0{,}52}$$

According to Rigon et al. (2022)

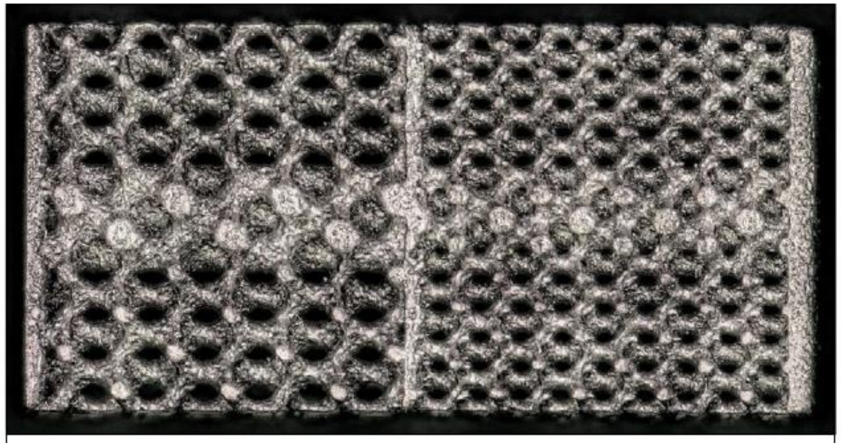
l is a length parameters and can be correlated to the martensite lath width or alpha grains in Ti6Al4V



Conclusions

- High to very high cycle fatigue of materials in the process-related condition is always related to a competition and / or a combination of notch effects on different length scales
- Slightest changes in the process parameter settings can have a significant effect on the fatigue strength
- In order to fully exploit fatigue strength in the high to very high cycle range of materials in processed conditions generalized S-N curves in combination with safety factors (as are suggested in many fatigue assessment directives) do not mirror the potential of process optimization strategies

While a basic understanding of the true fatigue mechanisms are essential, to predict the VHCF strength of real components in process-related states this is only the tip of the iceberg!



Many thanks to the members of my team in Dresden involved in the work presented!

Many thanks to YOU for listening!

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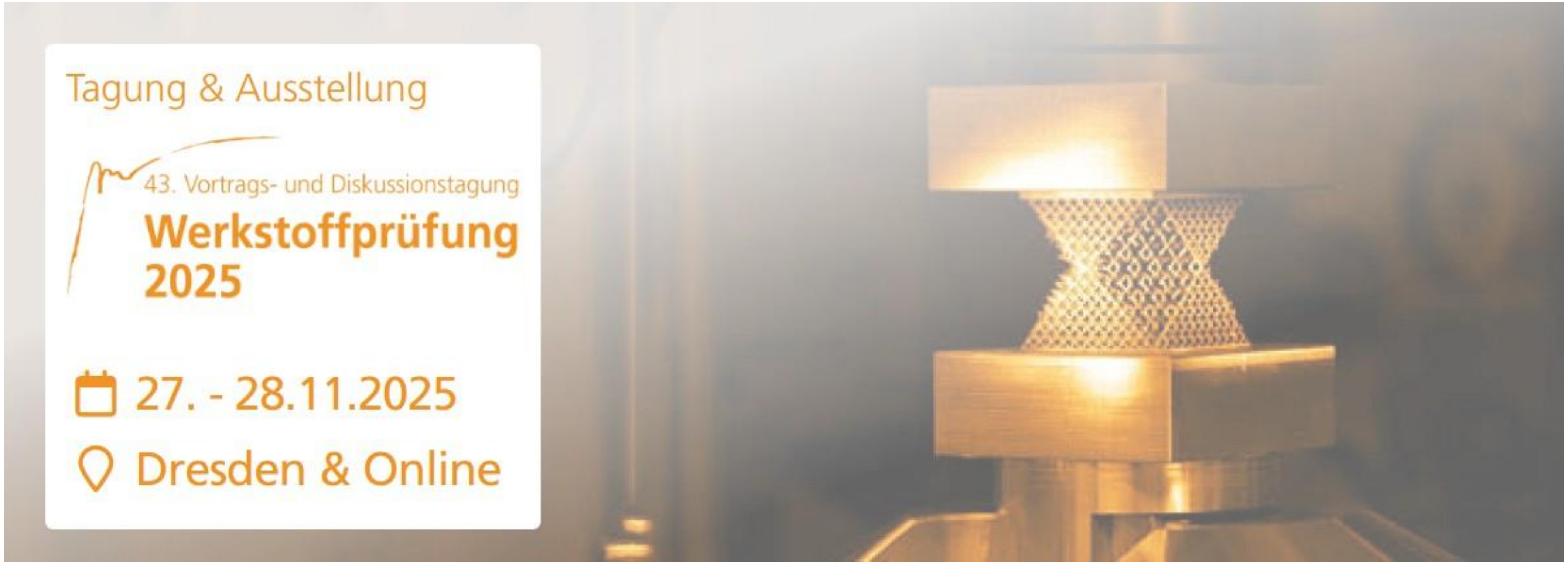
Hope to see you again in Dresden in 2025!



Many thanks to YOU for listening!

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