



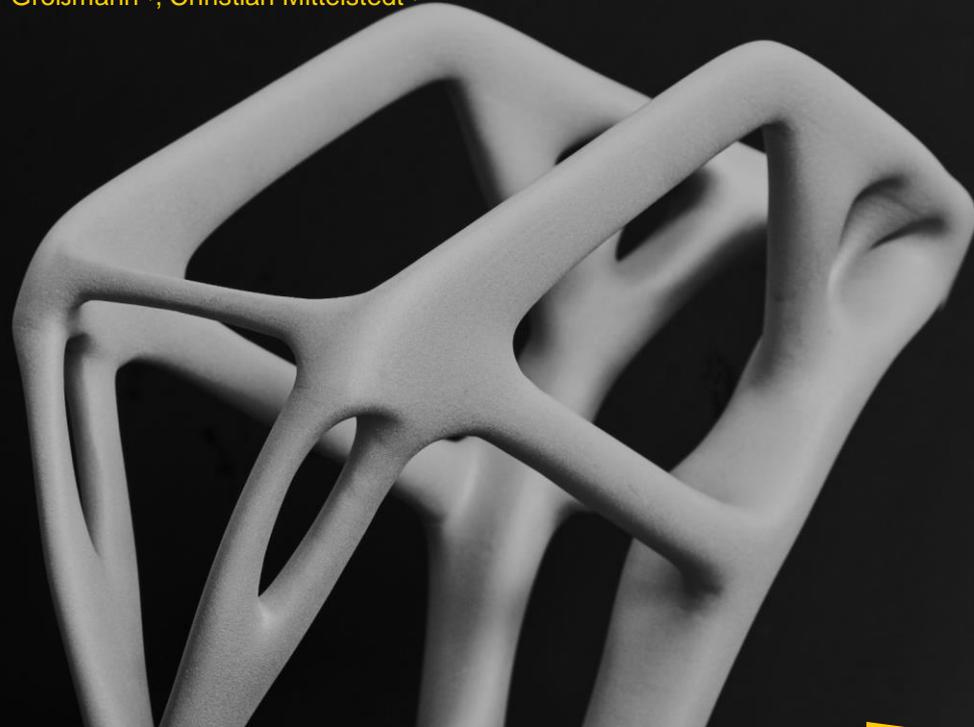
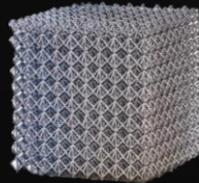
Beitrag zur zuverlässigen Implementierung von additiv gefertigten zellulären Strukturen in Leichtbaustrukturen

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DIGITAL



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Fachbereich Maschinenbau

Fachgebiet Konstruktiver Leichtbau und Bauweisen (KLuB)

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Additive Fertigung

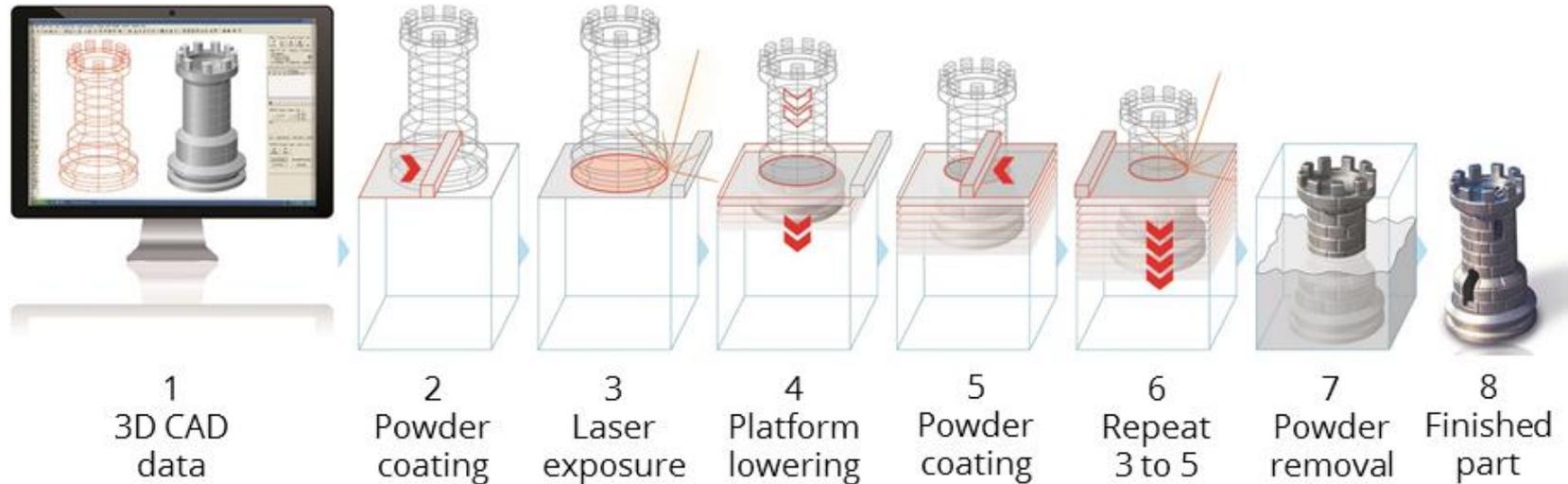
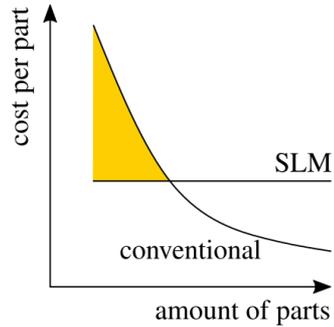


Image source: EOS GmbH

Warum die additive Fertigung?

Integrales Design, Weight Saving, Plug & Play, Funktionsintegration



Stahl 155 g



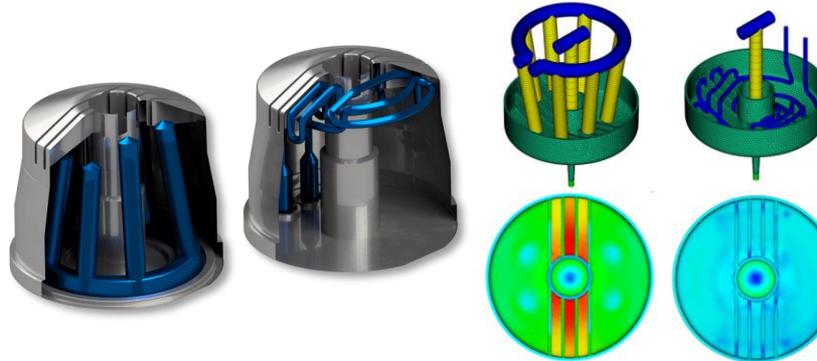
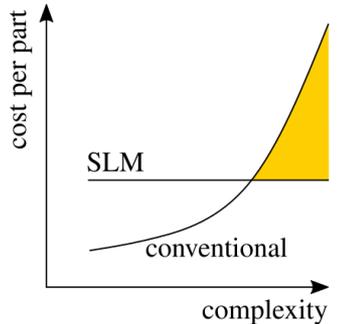
Titan 70 g



Ersparnisse

- -55% Gew. / St.
- 72.5 kg / AC
- 2 M€

➤ Roland Berger Strategy Consultants, München (2013)



- -15% Zykluszeit
- Produktivität
- Qualität

➤ Gries et al., Materials 14, 3434 (2021)

Topologieoptimierung und Design for Manufacturing

➤ Großmann et al., MSE Kongress, Digital (2020)

Requirement list

- Manufacturing Restrictions
- Material
- Loads
- Factors of Safety
- Allowed Stresses / Strains

Topology Optimization

- Design- / Non-Design Space
- FE-model with load / design-variable / target-function
- Parameter study

Interpretation

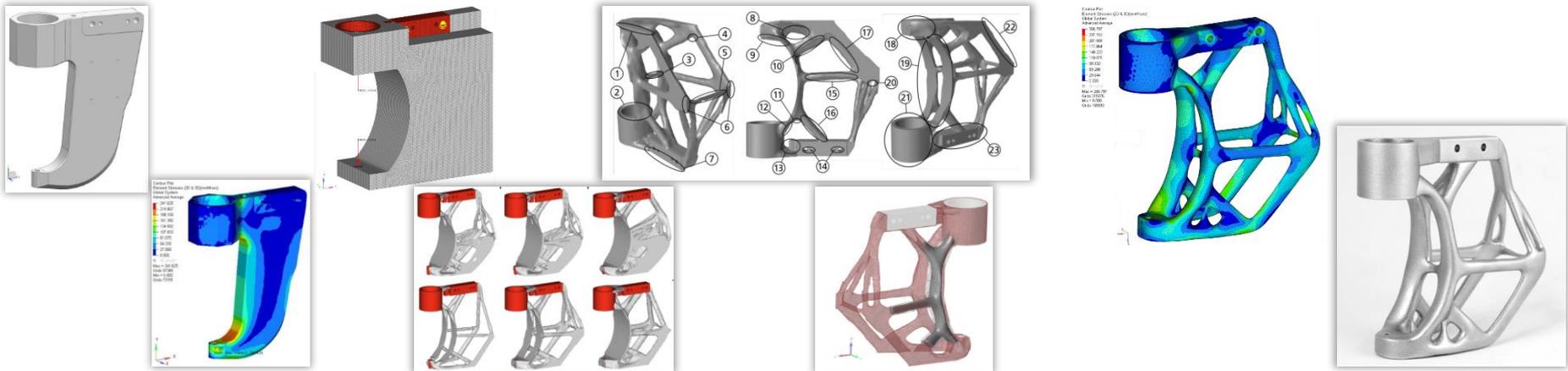
- Design guidelines
- Manufacturing restrictions
- Load case-based design

Re-Analysis

- FE-model
- Stress analysis according to requirement list

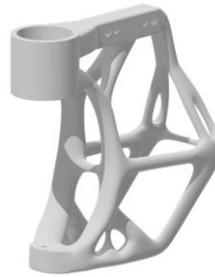
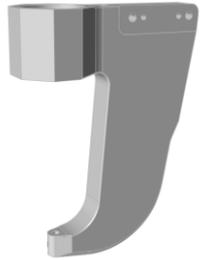
Final Design

- Manufacturing
- Post-processing
- Testing
- Integration



Topologieoptimierung und Design for Manufacturing

➤ Großmann et al., MSE Kongress, Digital (2020)



Conventional



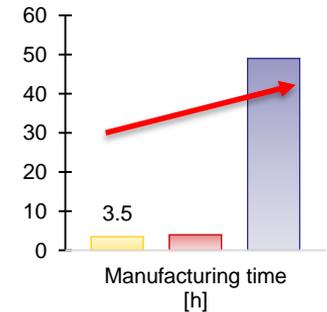
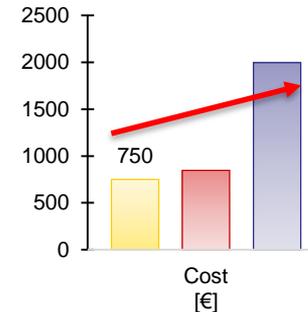
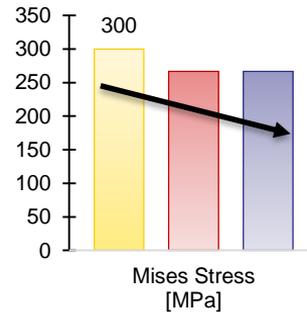
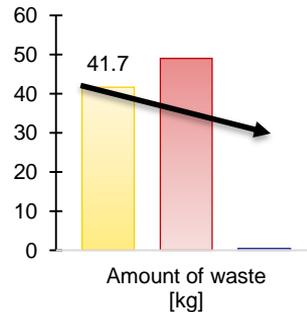
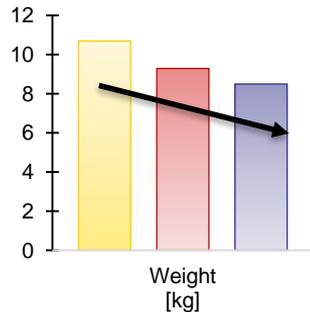
Milling Optimization



AM Optimization

Fazit

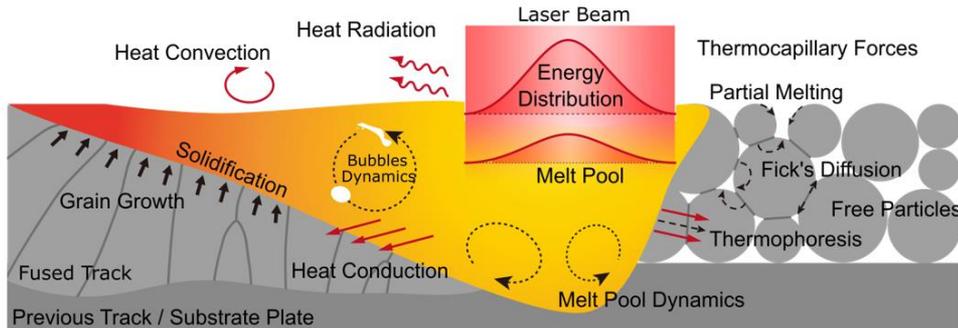
- AM-verbessertes mechanisches Verhalten
- Ökonomische Wettbewerbsfähigkeit?
 - ➔ Zelluläre Strukturen
 - ➔ Prozessgetriebenes Design (*Melt Pool Control*)



Leichtbau- und Produktivitätssteigerungen

➤ Großmann et al., MSE Kongress, Digital (2020)

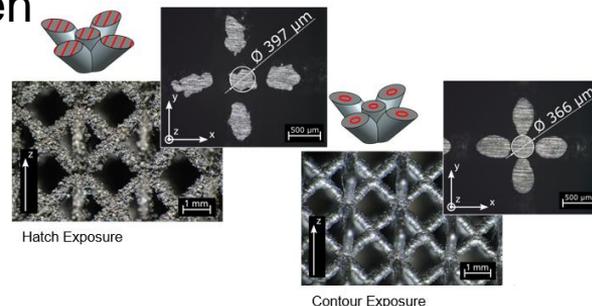
• Schmelzbadkontrolle



Bis zu + 840% Volumenrate
durch Parametervariation

➤ Metelkova et al., Additive Manufacturing 23, 161-169 (2018)

• Gitterstrukturen

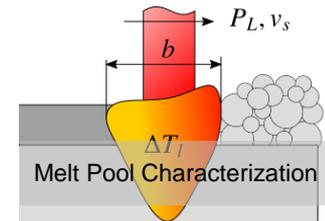
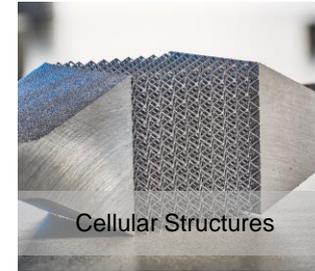
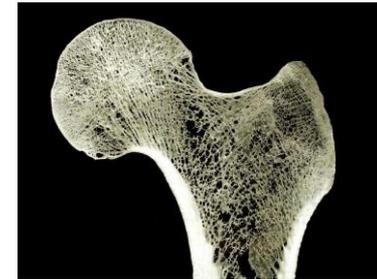
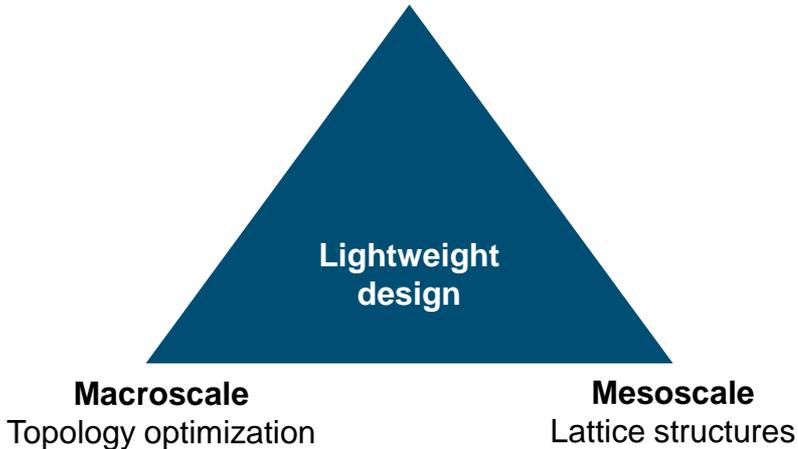


-81% Fertigungszeit durch
Anpassung der Belichtungsstrategie

➤ Abele et al., Rapid Prototyping Journal 21, 117-127 (2015)

Vision / Strategie

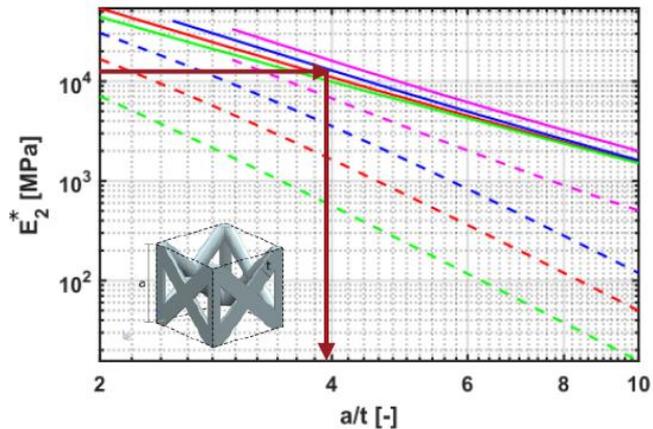
- Großmann et al., MSE Kongress, Digital (2020)
Manufacturing process
Laser driven design



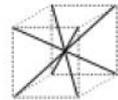
- Theoretische Ermittlung mechanischer Eigenschaften von Leichtbaustrukturen
- Experimentelle Validierung und Prüfung (quasi-statisch und dynamisch)

Betrachtete Gitterstrukturen

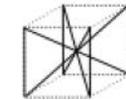
- Strebenbasierte Gitterstrukturen
 - Mathematische Formulierung
 - Methodische Entwicklung von Ansätzen
 - Einstellbarkeit der Eigenschaften



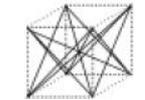
-- bcc



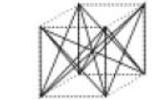
— bcc_z



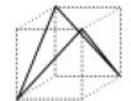
- - f₂ bcc



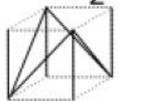
— f₂ bcc_z



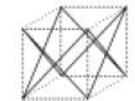
- - fcc



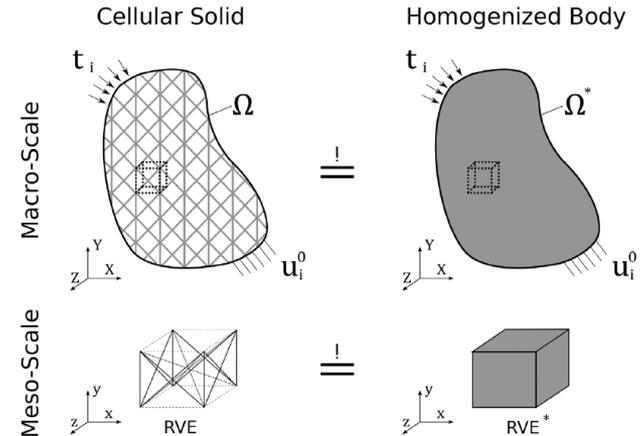
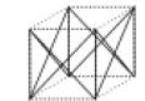
— fcc_z



- - f₂ cc



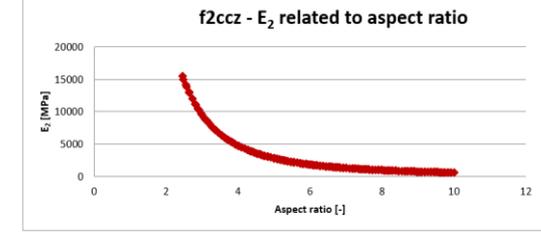
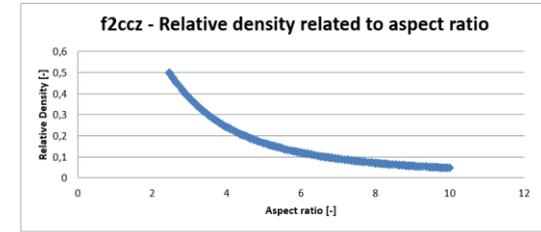
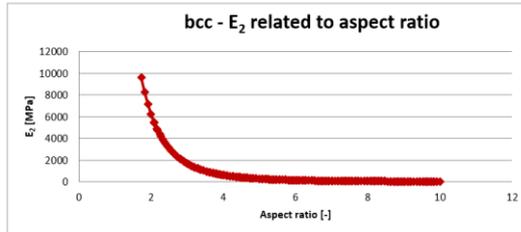
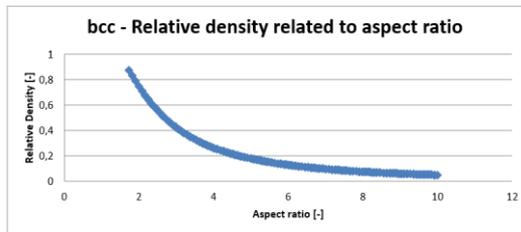
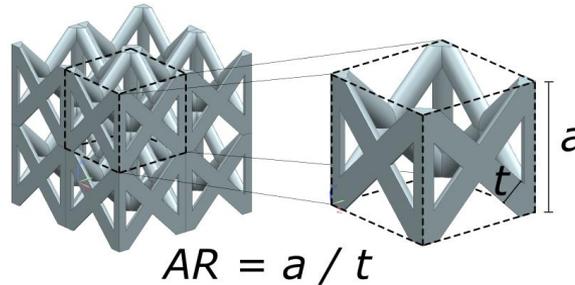
— f₂ cc_z



➤ Souza et al., Additive Manufacturing 23, 53-69 (20180)

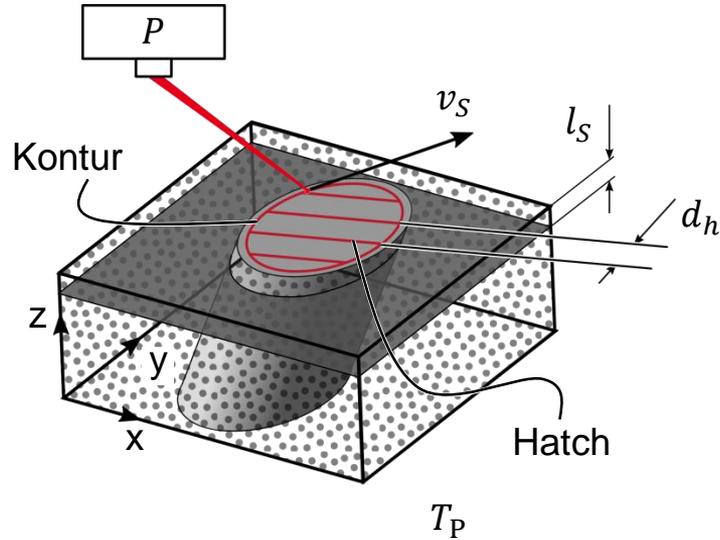
Betrachtete Gitterstrukturen

- Größenordnung → Aspektverhältnis



- Strukturabhängig
- AR zwischen 4 & 10
- Beispiel
 - AR = 8
 - a = 3 mm
 - t = 375 μ m

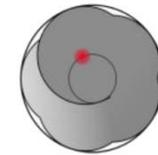
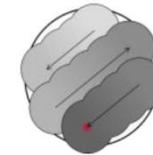
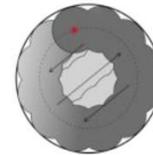
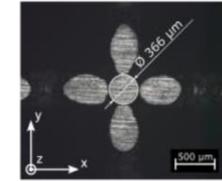
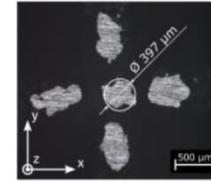
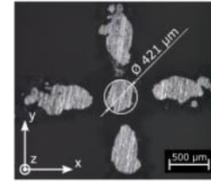
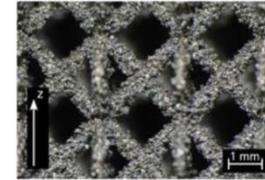
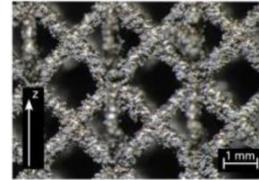
Herstellung von Gitterstrukturen



Kontur / Hatch

Hatch

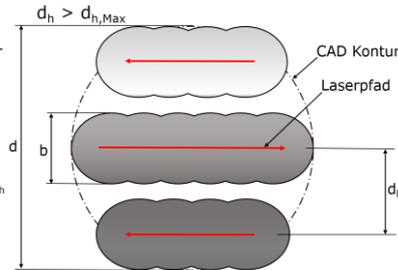
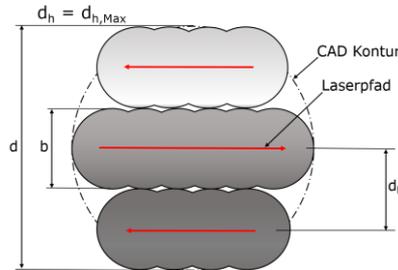
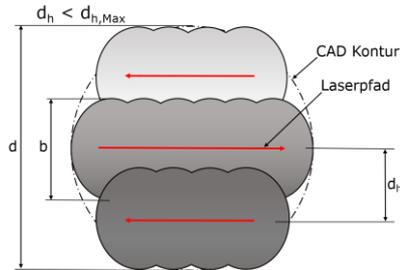
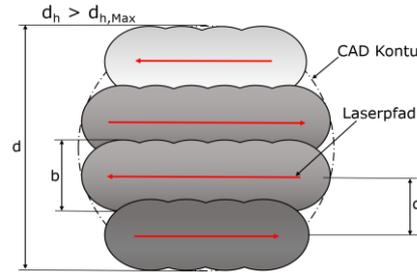
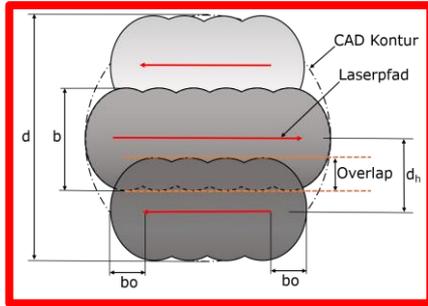
Kontur



Kontrollierte Herstellung zuverlässiger Gitterstrukturen? ($t < 1\text{mm}$)

Herstellung von Gitterstrukturen

Hatch



Vektoranzahl n

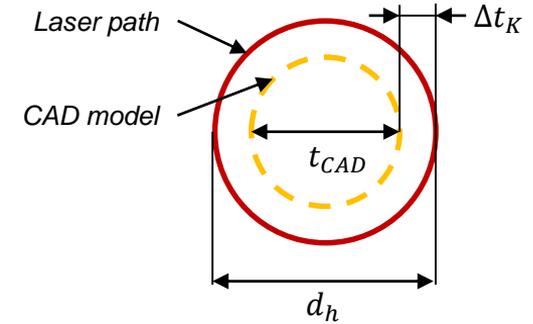
Offset bo

Linien-Energie E_l

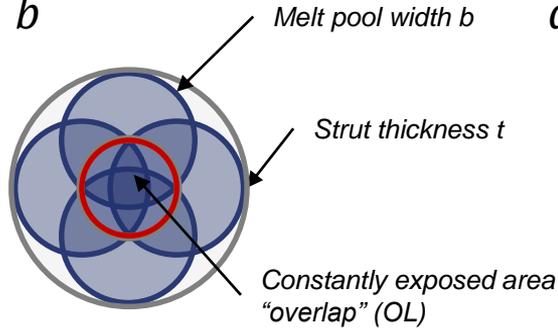
Herstellung von Gitterstrukturen

Kontur

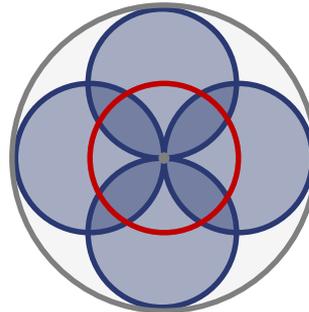
- Hatch distance für Kontur
 - Kontur offset Δt_K $d_h = t_{CAD} + 2 \cdot \Delta t_K$
- Für einen konstanten Parametersatz (P, v)



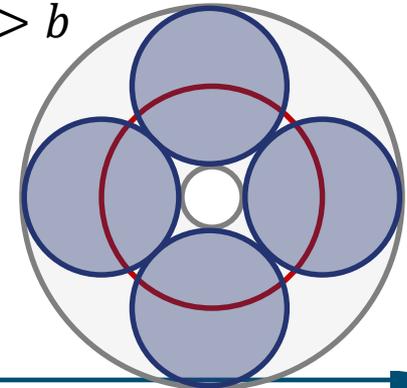
$$d_h < b$$



$$d_h = b$$

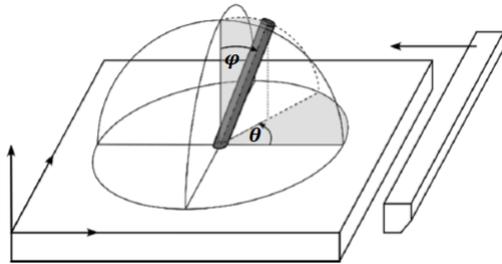


$$d_h > b$$



Herstellung – Strebenneigung

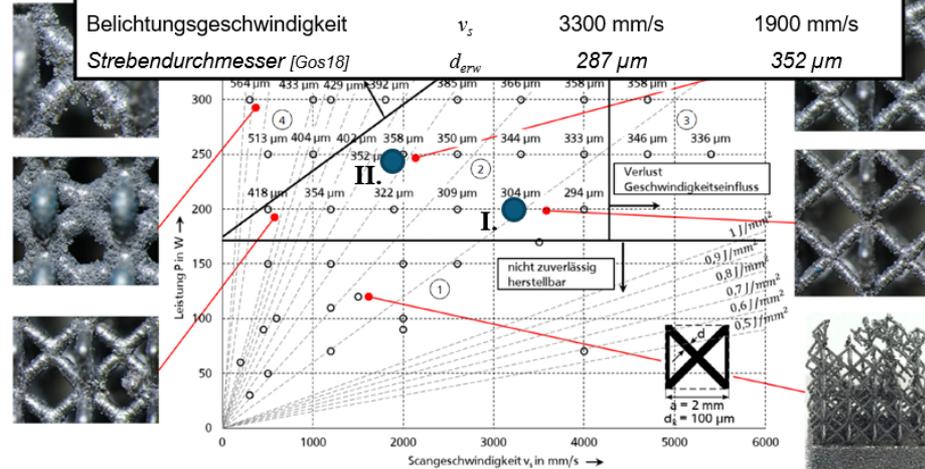
➤ Meyer et al., Manufacturing Letters, eingereicht



Polarwinkel φ

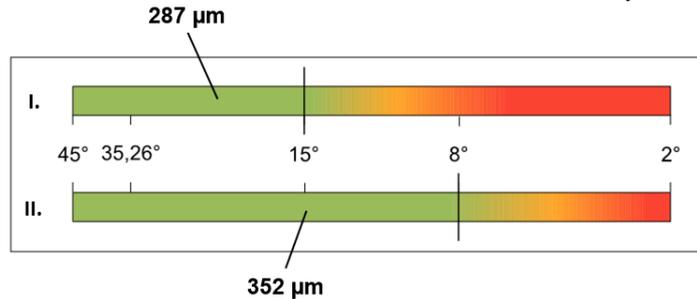
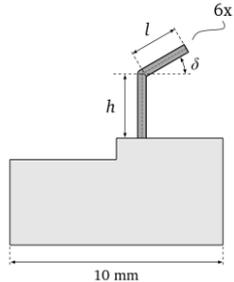
Drehwinkel um eine beliebige Achse in der xy-Ebene

Parametersatz		I	II
Laserleistung	P_L	200 W	240 W
Belichtungsgeschwindigkeit	v_s	3300 mm/s	1900 mm/s
Strebdurchmesser [Gos18]	d_{grw}	287 μm	352 μm



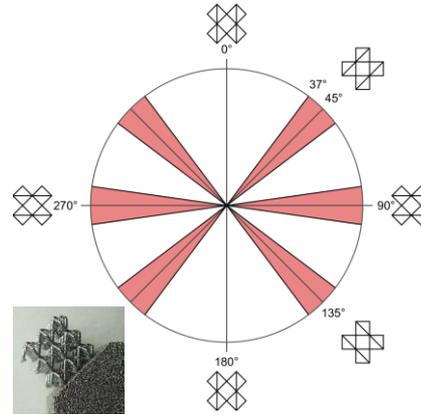
Herstellung – Strebenneigung

➤ Meyer et al., Manufacturing Letters, eingereicht



Parametereinfluss auf
Machbarkeit & Durchmesser

- Drehungswinkeln
- Gittertyp f_2cc_z
- $AR \leq 8,5$

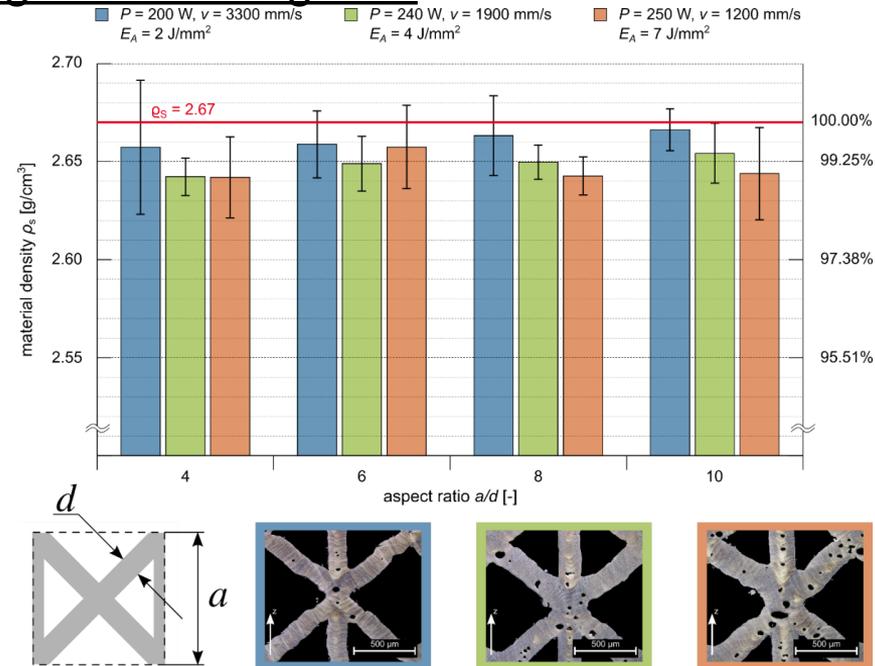


Einfluss des Neigungswinkels auf
mechanischen Eigenschaften

Herstellung – Defekte in Gitterstrukturen

➤ Meyer et al., MSE Kongress, Digital (2020)

Parameterabhängige Porositätsgehalt

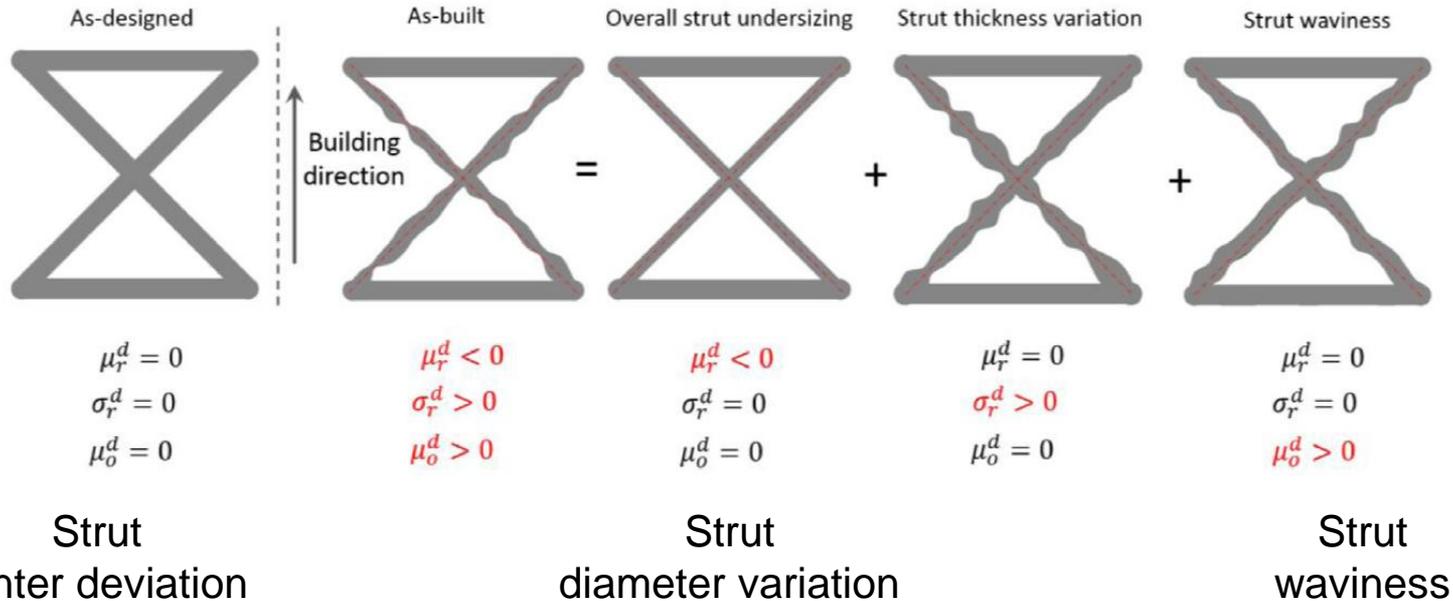


➤ Großmann et al., Mat. Sci. Eng. A 766, 138356 (2019)

Herstellung – Defekte in Gitterstrukturen

➤ Meyer et al., MSE Kongress, Digital (2020)

Abweichung der Maßhaltigkeit

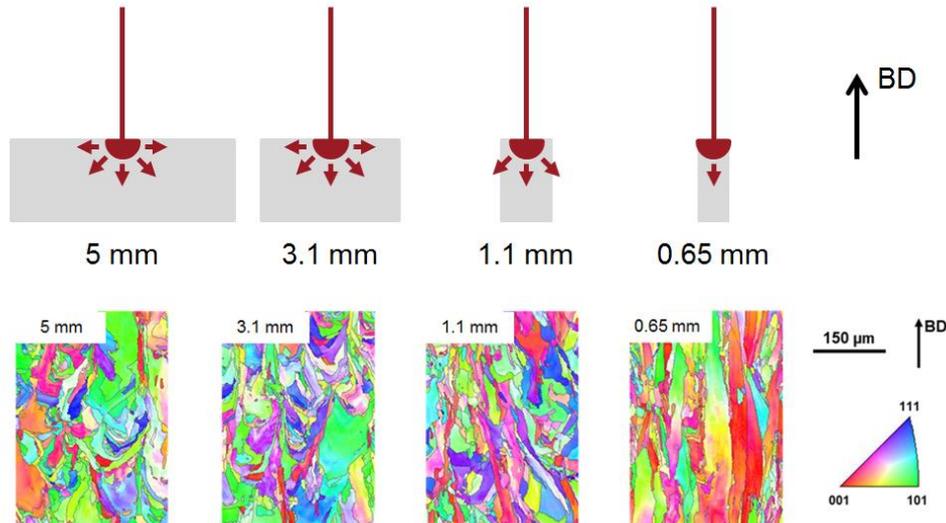


➤ Liu, L et al., *J. of Mech. & Phy. of Sol.* 107, 160-184 (2017)

Herstellung – Defekte in Gitterstrukturen

➤ Meyer et al., Metals 10, 1442 (2020)

Miniaturisierungseffekt



Material-System	E_{exp}^* (MPa)	E_{ana}^* (MPa)	Δ (%)
316L-bcc	339	367	-7.6
316L-f2ccz	2824	8849	-68.1
Ti6Al4V-bcc	542	463	17.1
Ti6Al4V-bcc-HT	504	463	8.9
Ti6Al4V-f2ccz	3296	4150	-20.6
Ti6Al4V-f2ccz-HT	3113	4150	-25.0

Temperaturgradienten

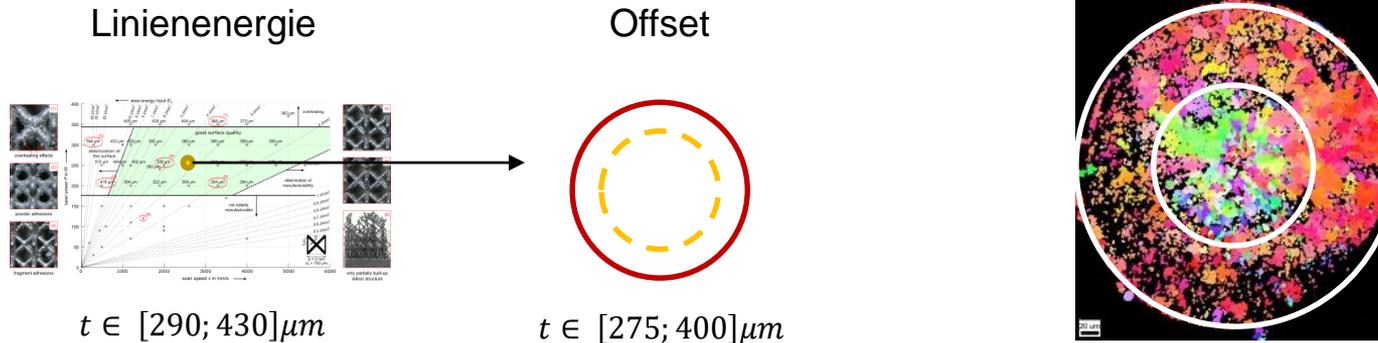


Material- & Neigungsabhängige
Eigenschaftsminderung

Herstellung – Defekte in Gitterstrukturen

➤ Meyer et al., MSE Kongress, Digital (2020)

Miniaturisierungseffekt & Strebendurchmesservariation



Parameterabhängige

- Rauheit
- Geometrie

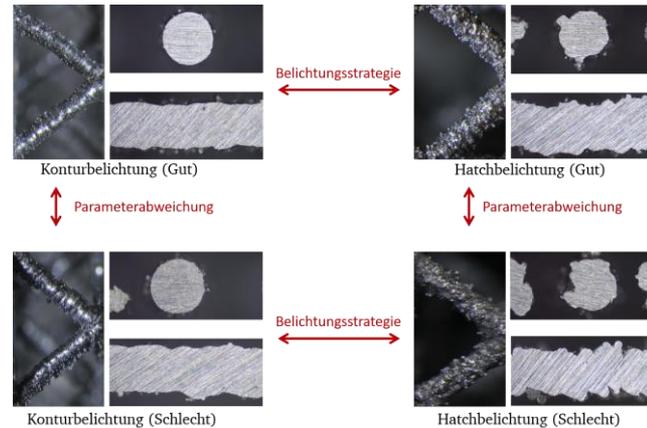
Parameterunabhängige

- Rauheit
- Durchmesser

Unterschiedliche Belichtungszone

- Hoher Energieeintrag
- Kleine Hatchabstände (hoher Überlapp)
- In-situ Wärmebehandlung?

Herstellung – Defekte in Gitterstrukturen



- Cao et al., Composites Part B: Engineering 194, 108030 (2020)
- Liu et al., J. of Mech. & Phy. of Sol. 107, 160-184 (2017)
- Li et al., Materials & Design 192, 108709 (2020)

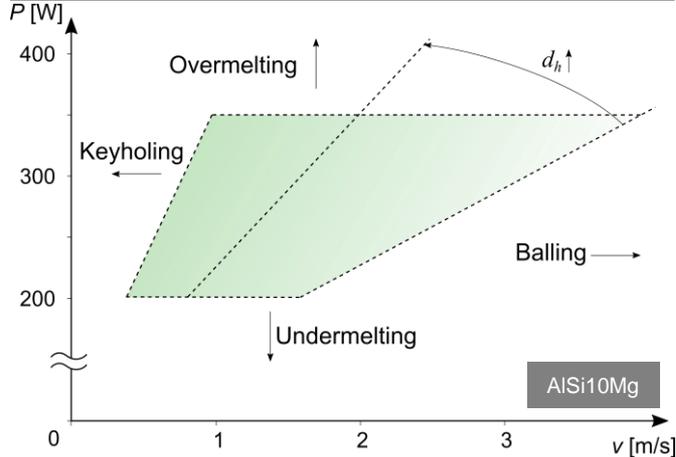
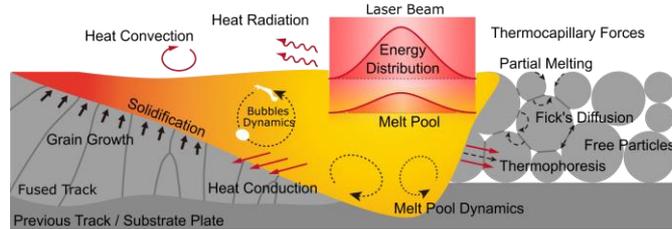
- Versuche
- EBSD
- μ CT
- ...

Notwendigkeit einer multi-skala Quantifizierung der prozessbedingten mechanischen Eigenschaften (inkl. Belichtungsstrategie)

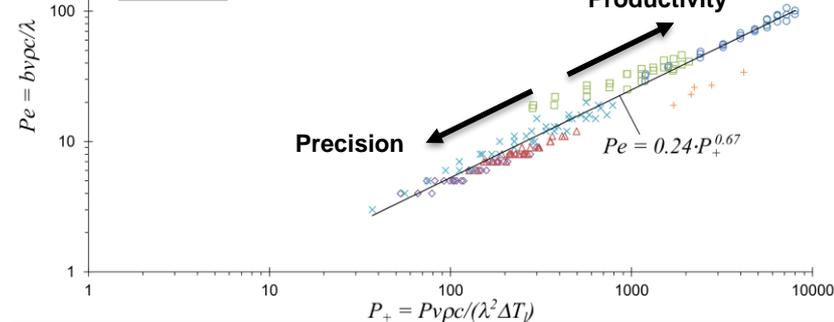
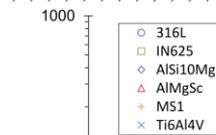
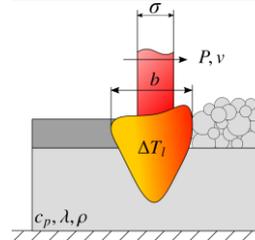
Herstellung – Skalierungsgesetz

➤ Großmann et al., MSE Kongress, Digital (2020)

Von einem materialabhängigen Prozessfenster...



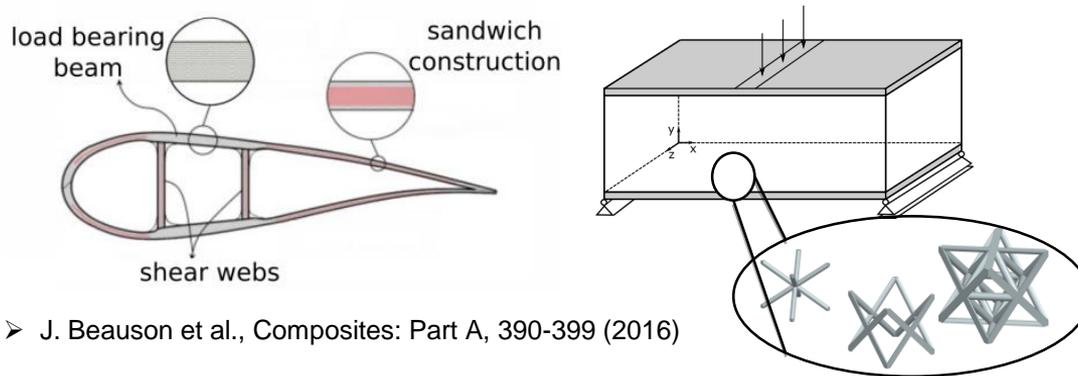
... bis zu prozessspezifischen dimensionslosen Zahlen



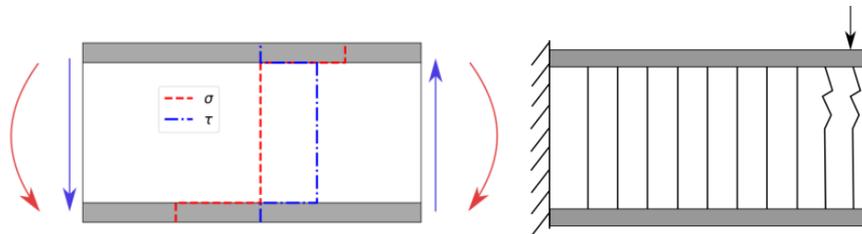
Konzepte - Gradierung

➤ Georges et al., GAMM Annual Meeting, Kassel (2021)

Spannungshomogenisierung & Gewichtsreduktion

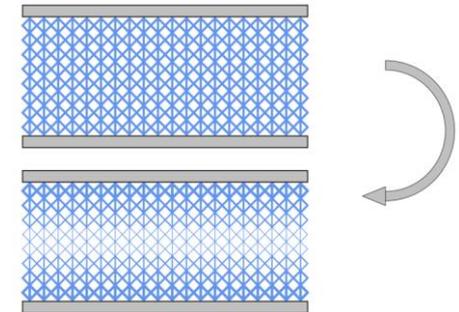


➤ J. Beauson et al., Composites: Part A, 390-399 (2016)



- Spannungsspitzen
 - Krafteinleitung
 - Stützpunkte

- Platzhalter
 - Biegebelastung
- Tragfähig
 - Querkräften
 - Krafteinleitung

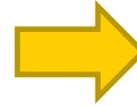
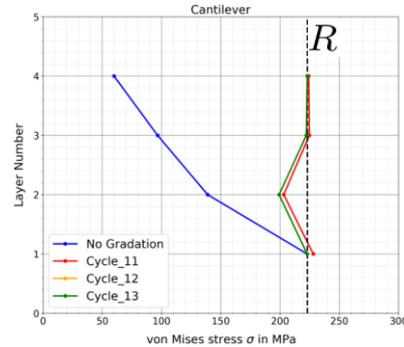
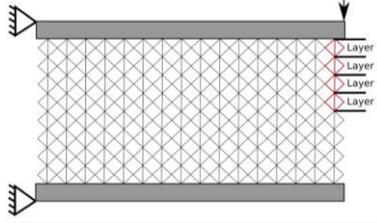


Konzepte - Gradierung

➤ Georges et al., GAMM Annual Meeting, Kassel (2021)

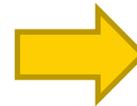
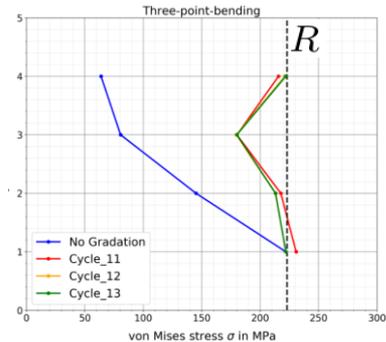
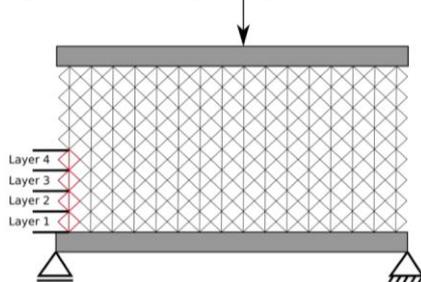
Spannungshomogenisierung & Gewichtsreduktion

- Einseitig eingespannter Balken



38%
Gewichtsreduktion

- Dreipunktbiegung

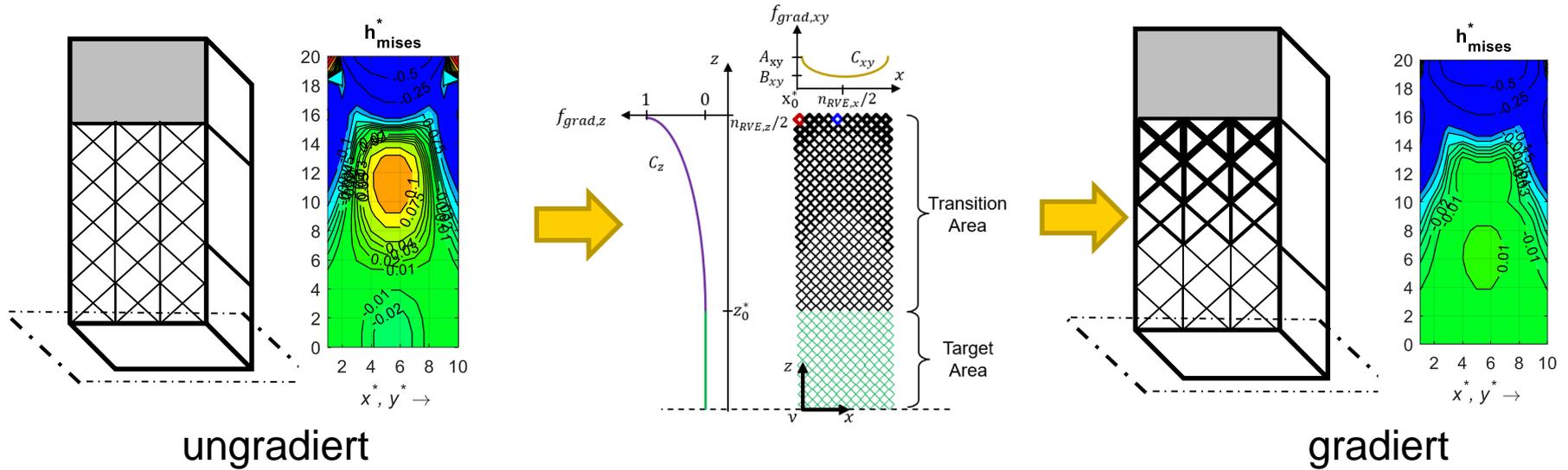


36%
Gewichtsreduktion

Konzepte - Gradierung

➤ Meyer et al., in Vorbereitung

Spannungshomogenisierung & Krafteinleitung

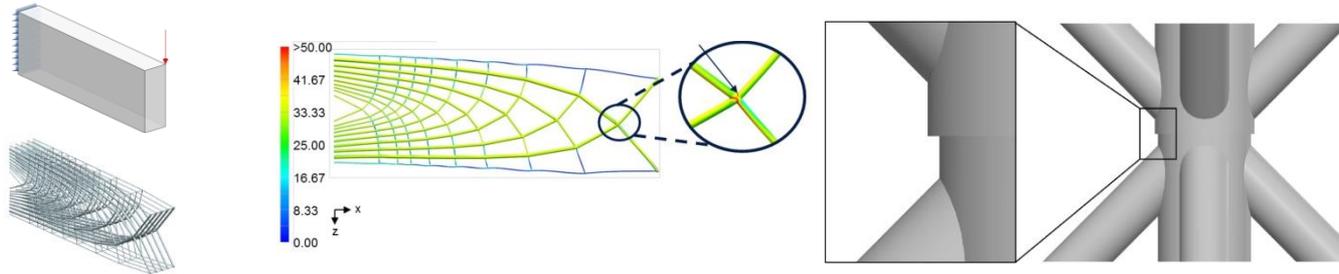


$$f_{grad}(x^*, y^*, z^*) = 1 + \left[A_{xy} + (B_{xy} - A_{xy}) \cdot \left(\frac{\min(x^*, y^*) - x_0^*}{n_{RVE,x}/2 - x_0^*} \right)^{C_{xy}} \right] \cdot \left(\frac{z^* - z_0^*}{n_{RVE,z}/2 - z_0^*} \right)^{C_z}$$

Konzepte - Kerbwirkungsverringering

➤ Meyer et al., ICMAE Konferenz, Digital (2021)

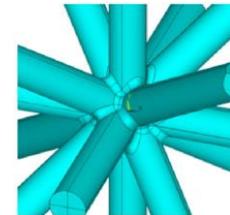
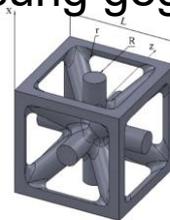
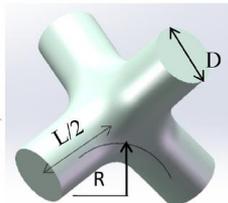
- Nicht nur herstellungsbedingte Kerben



Beste Lösung?

➤ Teufelhart S., Diss. TU-München (2016)

- Herkömmliche Designlösung gegen Kerben = „Fillet Radius“

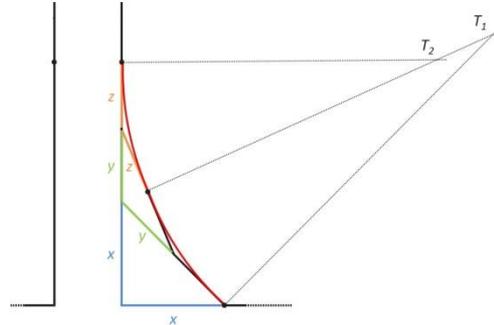
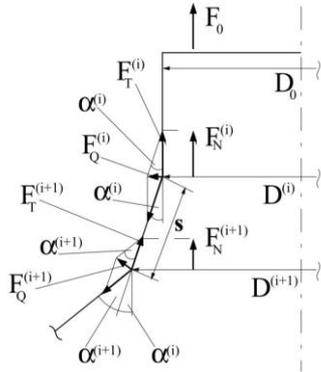
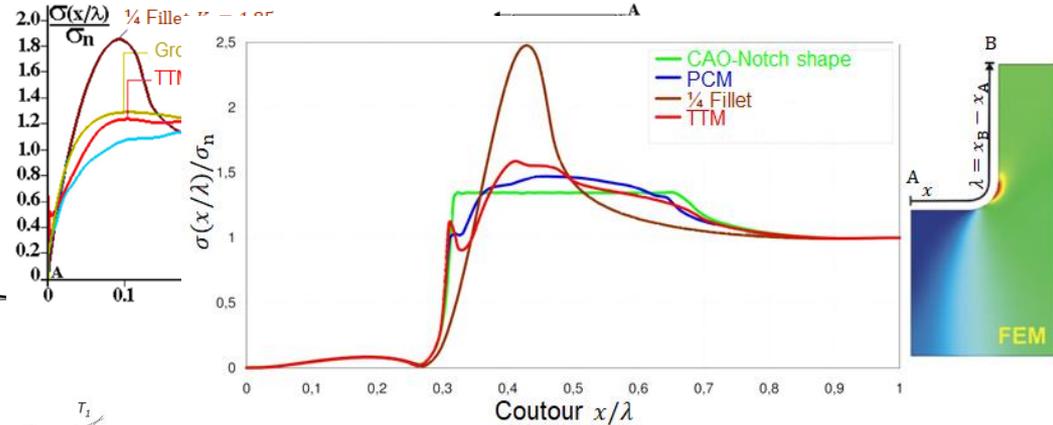
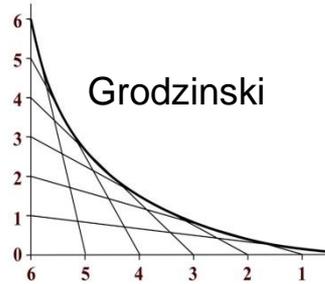
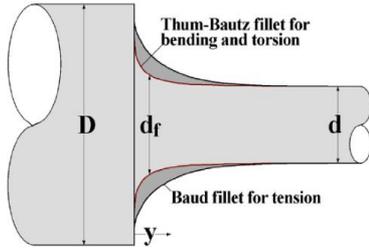


➤ Refai et al., Mech. Adv. Mat. & Struct. 334, 1966-1982 (2019)

➤ Li et al., Mat. & Des. 192, 108709 (2020) ➤ Savio et al., Int. J. Interactive Design & Manuf. 13, 263-276 (2019)

Konzepte - Kerbwirkungsverringering

• 2D Kerbspennungsansätze

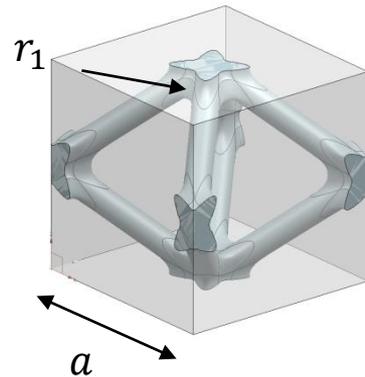
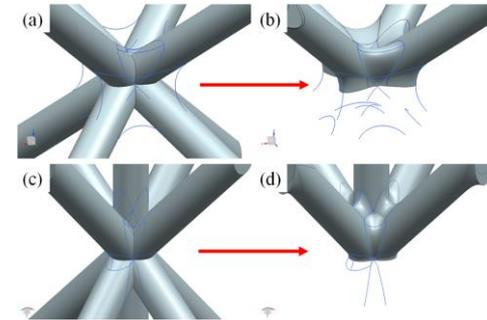
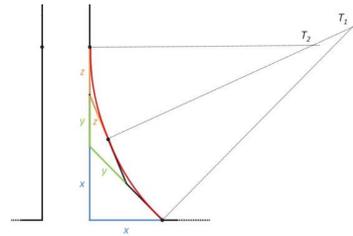
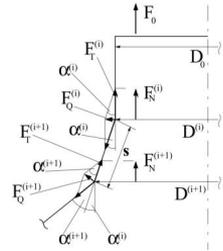


- Castro et al., *Theo. & Appl. Fr. Mech.* 84, 72-85 (2016)
- Zelenika et al., *MEDSI Proc.*, 04-25 (2014)
- Scherrer M., *Diss. TU-Karlsruhe* (2004)
- Sörensen J., *Diss. TU-Karlsruhe* (2008)
- Mattheck C., *Eng. Fract. Mech.* 73, 1732-1742 (2006)

Konzepte - Kerbwirkungsverringering

➤ Meyer et al., ICMAE Konferenz, Digital (2021)

- Anwendung von Ansätze an Gitterstrukturen

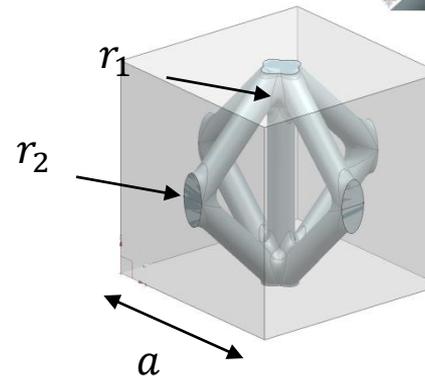


$$a = 3 \text{ mm}$$

$$d_m = 370 \text{ } \mu\text{m}$$

$$r_1 = \gamma \cdot d_m$$

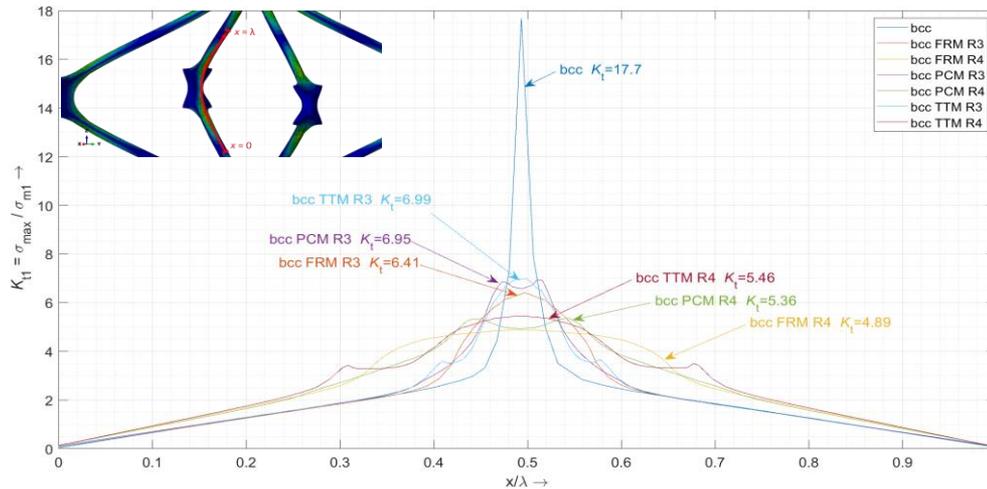
$$r_2 = \theta \cdot d_m$$



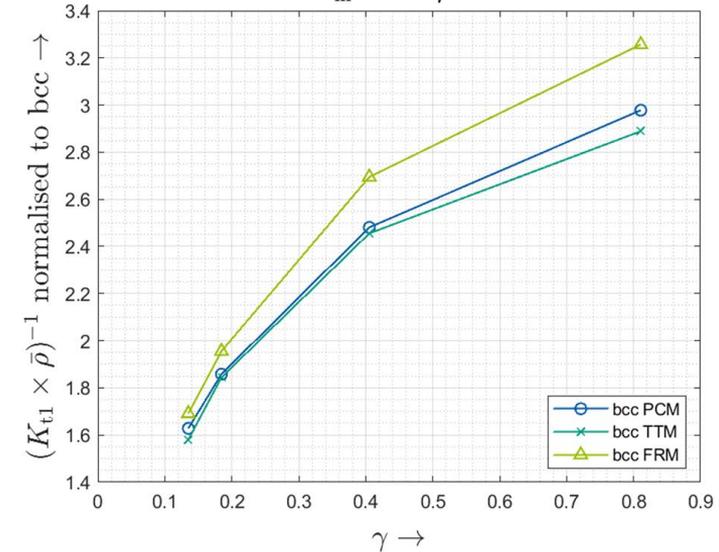
Konzepte - Kerbwirkungsverringering

➤ Meyer et al., ICMAE Konferenz, Digital (2021)

- Vergleich zwischen Ansätzen und der Originalstruktur (Bsp. bcc)



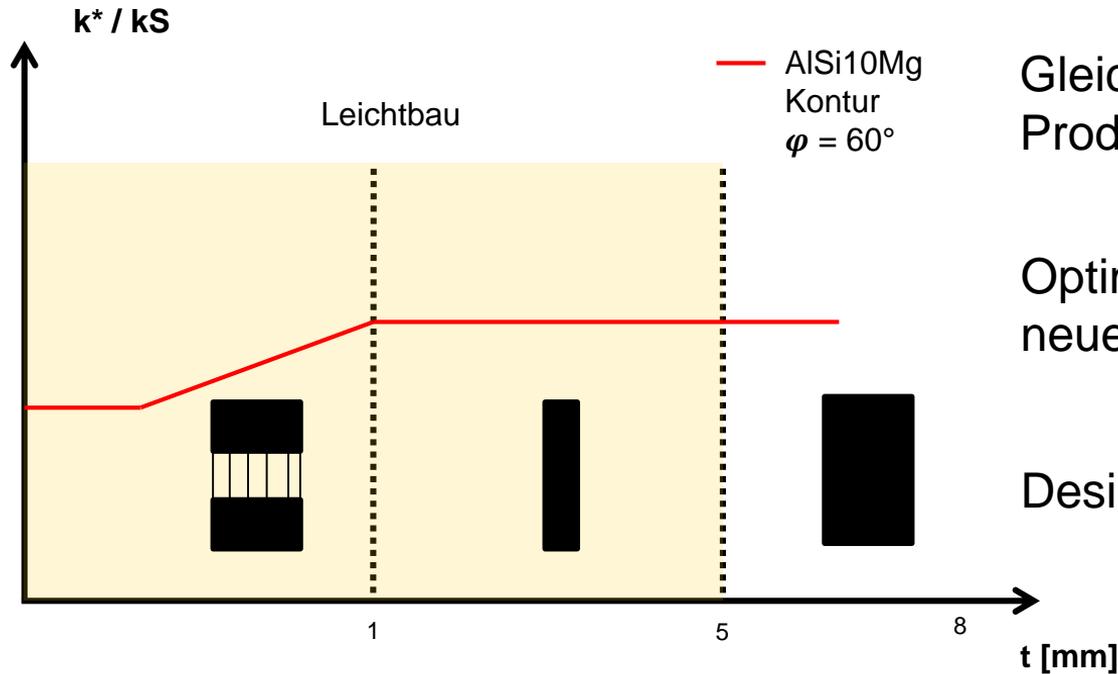
$d_m = 370 \mu\text{m}$



Versprechende Ergebnisse

➤ Meyer et al., in Vorbereitung

Langfristiges Ziel



Gleichzeitige Qualitäts- und Produktivitätssteigerungen

Optimierungspotential auf einem neuen Niveau

Designrichtlinien & Nachweismethodik

Langfristiges Ziel

➤ Großmann et al., MSE Kongress, Digital (2020)

Kontrollierte Prozessführung

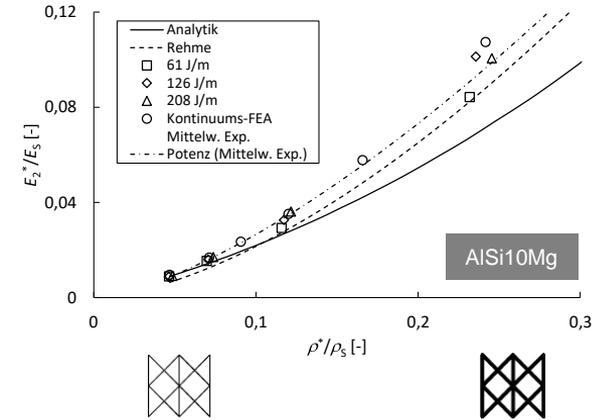
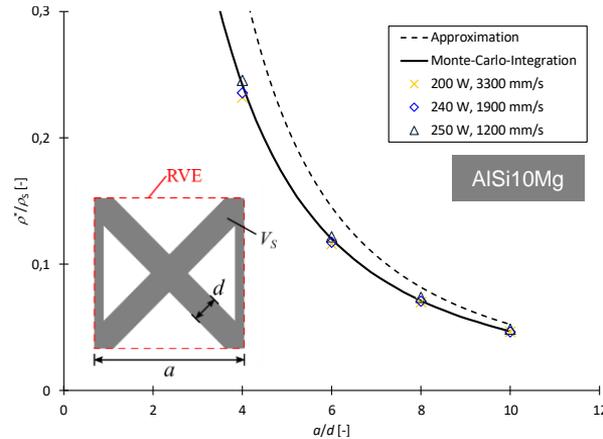
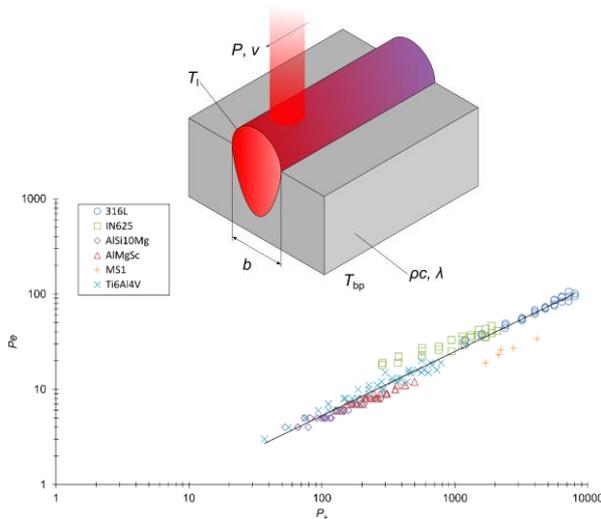
$$Pe = 0.24 P_+^{0.67}$$

Einstellbare Geometrie

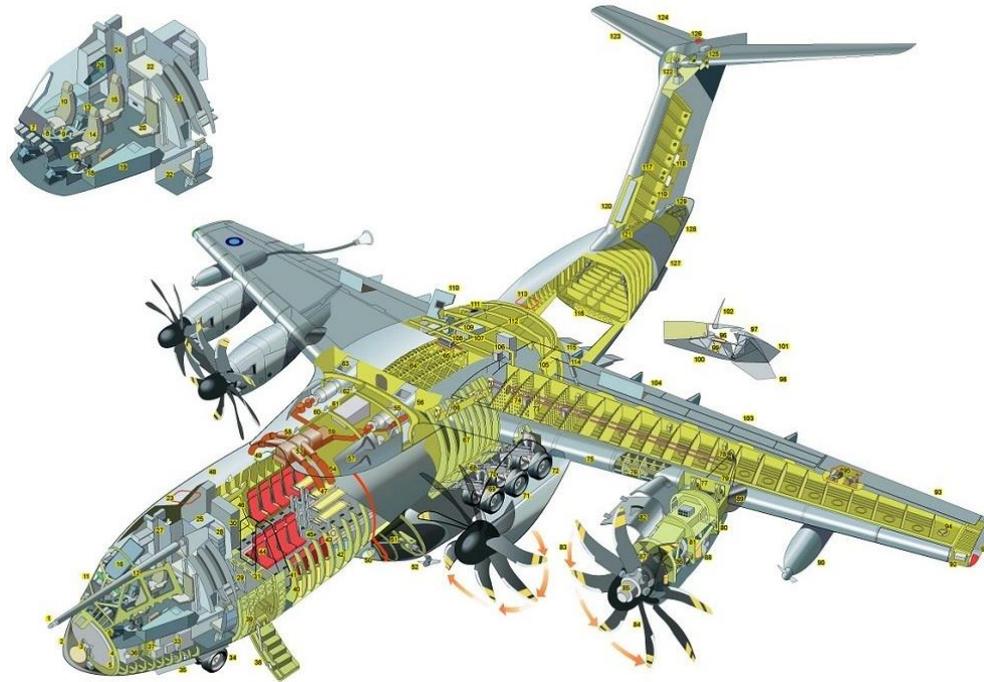
$$\frac{\rho^*}{\rho_s} = 2.56 \left(\frac{a}{d}\right)^{-1.73}$$

Vorhersehbare mechanischen Eigenschaften

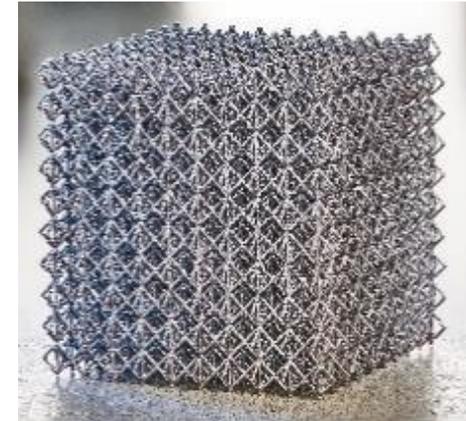
$$\frac{E_2}{E_s} = 0.77 \left(\frac{\rho^*}{\rho_s}\right)^{1.46}$$



Langfristiges Ziel



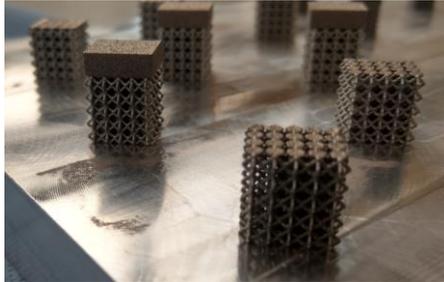
Primärstrukturen mit integrierten Gitterstrukturen



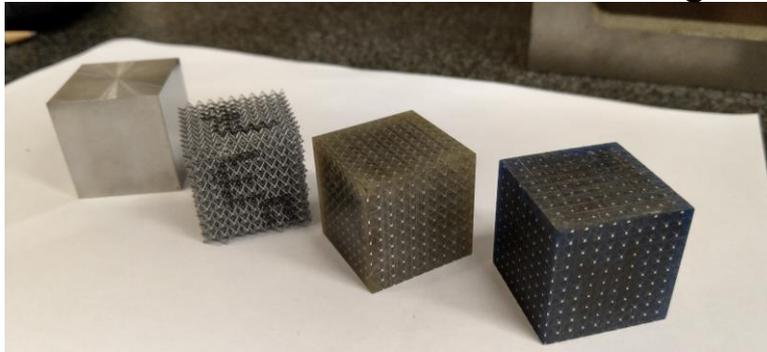
➤ <https://aerospaceengineeringblog.com/aircraft-structures/>

Andere aktuellen AM Themen

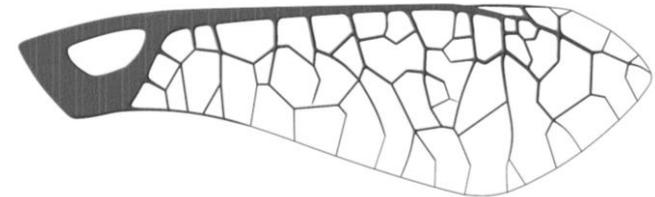
- Stützstrukturfreies konstruieren & drucken



- Hybride Strukturen & Funktionsintegration



Und viel mehr...



Sprechen Sie uns an!

Vielen Dank für Ihre Aufmerksamkeit



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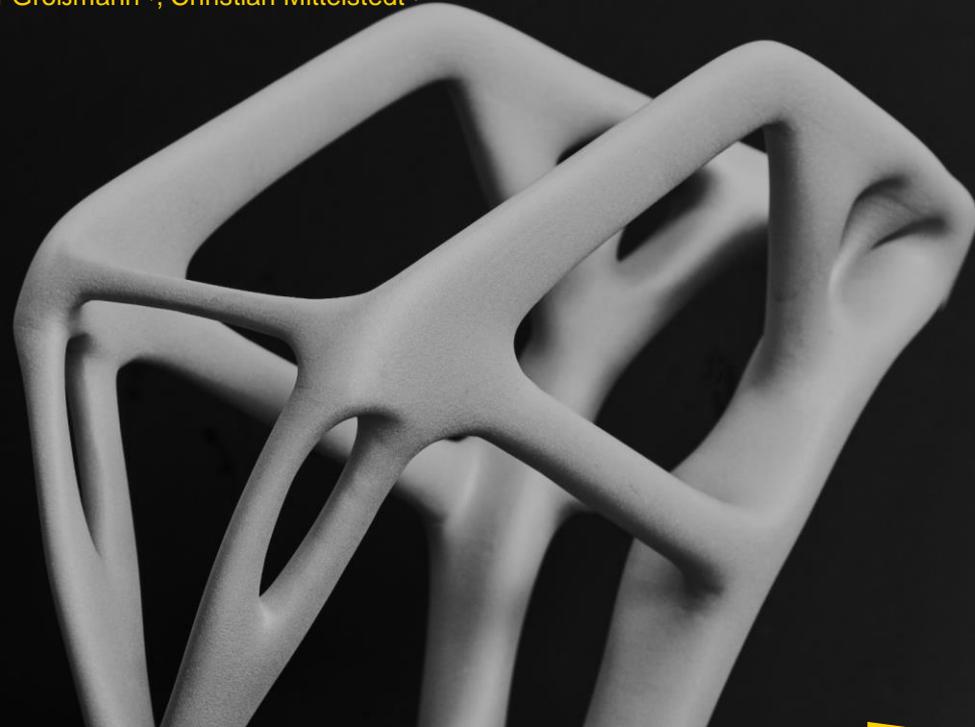
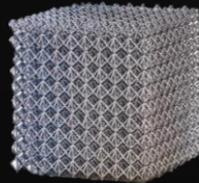
Beitrag zur zuverlässigen Implementierung von additiv gefertigten zellulären Strukturen in Leichtbaustrukturen

Guillaume Meyer^{1*)}, Hussam Georges²⁾, Matthias Greiner¹⁾, Alexander Großmann¹⁾, Christian Mittelstedt¹⁾

Deutscher Luft- und Raumfahrtkongress 2021

31. August – 02. September 2021

DIGITAL



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Fachbereich Maschinenbau

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