In-Situ Surface Roughness Measurement of Laser Beam Melted Parts – a Feasibility Study of Layer Image Analysis

Joschka zur Jacobsmühlen¹, Stefan Kleszczynski², Alexander Ladewig³, Gerd Witt² and Dorit Merhof¹

¹RWTH Aachen University
²University of Duisburg-Essen
³MTU Aero Engines AG
Motivation of Studies

Laser Beam Melting of Metal Components

- Production of complex and individual components
- Of special interest for aerospace and aero engine industry
- First production lines established at MTU Aero Engines AG in Munich, Germany

High requirements
- quality assurance
- process stability
- reproducibility
Motivation

Surface Roughness

Target of optimization in LBM produced parts

- Reduce post-processing
- Optimize internal structures for which post-processing is impossible (e.g. channels)

Related Work

- Minimization of surface roughness (Yasa and Kruth, 2011)
- Identification of dependencies between roughness and process parameters (Strano, 2013)
- Inline 3D surface metrology using optical coherence tomography (Schmitt, 2013)

In-situ measurement is highly desirable

- Inspect surface roughness of internal surfaces
- Check fulfilment of design requirements
Layer Image Acquisition

zur Jacobsmühlen, J.; Kleszczynski, S.; Schneider, D. & Witt, G.
High Resolution Imaging for Inspection of Laser Beam Melting Systems
IEEE International Instrumentation and Measurement Technology Conference (I²MTC), 2013
Layer Images

5 mm

scan line: ca. 90 µm

1 pixel: 25…35 µm
Objective

Replicate physical surface roughness measurements

layer images

z

y

x

...
Objective

Replicate physical surface roughness measurements

segmented contour

layer images
Objective

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segmented contour

layer images
Objective

Replicate physical surface roughness measurements

- Extract surface profiles

layer images

segmented contour
Objective

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![Diagram showing segmented contour and layer images in 3D space with x, y, and z axes.]
Objective

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- Extract surface profiles

[Diagram of layered images with segmented contour]
Objective

Replicate physical surface roughness measurements

- Extract surface profiles
- Compute surface roughness
Outline

• Motivation
• Experimental Setup and Physical Measurements
• Segmentation of Part Contours
• Surface Profile Reconstruction
• Surface Roughness Measurements
• Results
• Discussion and Conclusion
Experimental Setup and Physical Measurements

EOSINT M270, NickelAlloy IN718

- 2x 12 faces for measurements (outside and inside), placed at multiples of 30°
- Measurement of $R_z$ (EN ISO 4287) using Mitutoyo SJ-400 profilometer:
  - divide each profile (A - C) into five segments
  - measure maximum peak-to-peak distance for each segment $R_z (i)$
  - compute average

$$R_z = \frac{1}{5} \sum_{i=1}^{5} R_z (i)$$

- Average of three $R_z$ measurements yields surface roughness for each pyramid face
- Part is built nine times: 216 measurements

Segmentation of Part Contours

- Goal: identify part boundary
- Powder appears as noise-like background
  - edge detection yields false positive edges
Segmentation of Part Contours

Difficult Regions
Segmentation of Part Contours: Edge Detection 1

Problems

- Multiscale results (fine to coarse)
- Many edges in powder regions (fine scale)
- Combine scales for optimum result

➢ But: no closed boundary!

Jacob, M. & Unser, M. 
Design of steerable filters for feature detection using canny-like criteria 
Pattern Analysis and Machine Intelligence, IEEE Transactions on, 2004, 26, 1007 -1019
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Segmentation of Part Contours: Edge Detection 2

Robust Detection

- Structured Forests for edge detection
  - Incorporate texture information
  - Edges correlate to subjective results

➢ Still no closed boundary!

Dollár, P. & Zitnick, C.
Structured Forests for Fast Edge Detection
*Computer Vision (ICCV), 2013 IEEE International Conference on*, 2013
Segmentation of Part Contours: Graph Cuts

Find Optimum Region Boundaries
Segmentation of Part Contours: Graph Cuts

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- Represent each image pixel as node in a graph
Segmentation of Part Contours: Graph Cuts

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• Represent each image pixel as node in a graph
• Edges are assigned weights
Segmentation of Part Contours: Graph Cuts

Find Optimum Region Boundaries

- Represent each image pixel as node in a graph
- Edges are assigned weights
  - High: strong link between neighbors: “don’t cut here”

![Graph Cut Diagram]

- part pixel
- powder pixel
- layer image
- strong link
Segmentation of Part Contours: Graph Cuts

Find Optimum Region Boundaries

• Represent each image pixel as node in a graph
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  – High: strong link between neighbors: “don’t cut here”
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Segmentation of Part Contours: Graph Cuts

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  - Low: weak link between neighbors: “cut allowed”
- Maximize flow between source $s$ and target $t$

![Diagram showing segmentation process with nodes representing pixels and edges with weights indicating strong and weak links.](image)
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**Weight Assignment**

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- Set low edge weight for pixels with edges („cut at edges“)
- Assign lower weights to outer regions („prefer outer boundary for cut“)

![Weight Assignment Diagram](image)
Segmentation of Part Contours

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Segmentation of Part Contours: Accuracy

Comparison of Edge Detectors

- Compared to manually annotated ground truth
- bidirectional local distance measure

Median: 39.1 µm

Median: 27.7 µm

Kim et al. Bidirectional local distance measure for comparing segmentations
*Medical Physics, 2012, 39, 6779-6790*
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Segmentation of Part Contours: Errors

Glare / shadows introduce edges inside of part
Surface Profile Reconstruction

Measurement Profiles

- Measure surface roughness of pyramid segments
- Use multiple profiles to capture roughness statistics
  - Additional rays at +/- 3° for each face
Surface Profile Reconstruction

Measurement of Internal and External Contour

- Intersections of radial rays and contours yield surface points
- Surface profile as difference of segmented contour and reference geometry
Surface Profile Reconstruction

Roughness Component from Filtration according to ISO16610-21

- Limit wavelength $\lambda_c = 2.5 \text{ mm}$
Surface Roughness Measurement

Visualization

• Determine $R_z$ from reconstructed surface profiles (ISO16610-21)
• Average three values of $R_z$ for each face
Results

Compare to profilometer measurements (gray)

- Normalized values for analysis of correlation
- Deviations are not captured correctly

No consistent correlation
Results

- Comparison against profilometer measurements
  - Absolute error [µm]
  - Error between normalized measurements

- Absolute error is very high (reference value range: 70…160 µm)
- Most normalized roughness values are too low (some large outliers)

Median: 131.3 µm
Median: -0.135
Discussion
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- Image resolution (20…30 µm/px) may be too low to capture roughness deviations (20…50 µm)
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Kleszczynski, S.; Ladewig, A.; Friedberger, K.; zur Jacobsmühlen, J.; Merhof, D. & Witt, G.
Position Dependency of Surface Roughness in Parts from Laser Beam Melting Systems
Proceedings of the 26th Internation Solid Freeform Fabrication (SFF) Symposium, 2015
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- Accuracy of segmentation: median error 27.7 µm
- Melt extensions below current layer are possible cause of roughness deviations
  - Cannot be captured by layer images

Conclusion
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- Image-based method for in-situ measurement of surface roughness
  - Replicates physical measurement method
  - Extract surface profiles from contour segmentation
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- High measurement errors compared to reference profilometry in experiments
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- Image-based method for in-situ measurement of surface roughness
  - Replicates physical measurement method
  - Extract surface profiles from contour segmentation
- High measurement errors compared to reference profilometry in experiments
- Not suitable for direct quantitative measurements
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