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Direct Metal Laser Sintering (DMLS) Contour Parameter Optimization DOE 1

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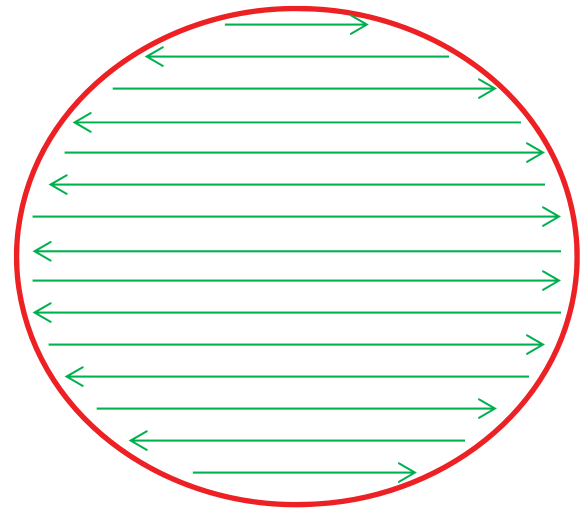
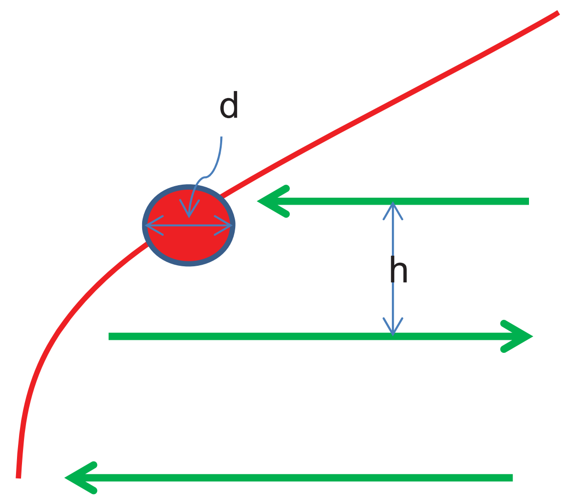
Scan parameter basics

Scan styles

- Two basic scan types in a typical part layer
  - Area scans
    - Also known as hatch or fill scans
    - Produce bulk of material in DMLS
    - Three critical parameters: beam speed (s, mm/s), spacing between individual passes of laser (h, mm), and laser power (P, W)
  - Line scans
    - Produce outer contours of parts and support structures
    - Area scans are made up of many line scans
    - Three critical parameters: beam speed (s, mm/s), beam diameter (d, mm), laser power (P, W)





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Global Energy Density (G)

- For area scans, an important quantity is the global energy density

$$G = \frac{P}{h * s} \qquad \left(\frac{J}{mm^2}\right)$$

- G is how much energy per unit area is incident on powder surface, and the most critical quantity in producing bulk material
- Porosity, stresses, microcracking are all describable as functions of G (within limits)

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Local Energy Density (L)

- For line scans, the corresponding quantity is the local energy density

$$\mathrm{L} = \frac{P}{d*s} \qquad\qquad (\frac{J}{mm^2})$$

- L is how much energy per unit area is incident on powder surface for line scans
- **In the context of a part contour, influences surface finish, stresses, and the presence of sub-contour porosity**
- In the context of support structure production, controls strength of supports
- In the context of an area scan, L acts as a secondary factor in the level of porosity, microcracking, and stresses

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Surface finish optimization example

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Surface finish and parameters: Example from literature

- “Investigation The Effect Of Particle Size Distribution On Processing Parameters Optimisation In Selective Laser Melting Process” by Liu, et al from Loughborough University
- Presented at SFF 2011
- Interestingly, they present an energy density that is L as calculated for an area scan
  - Varied L by varying beam diameter and scanning speed

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Results

- Increasing L, decreasing surface roughness
- Some evidence of slight increase at very high energy levels

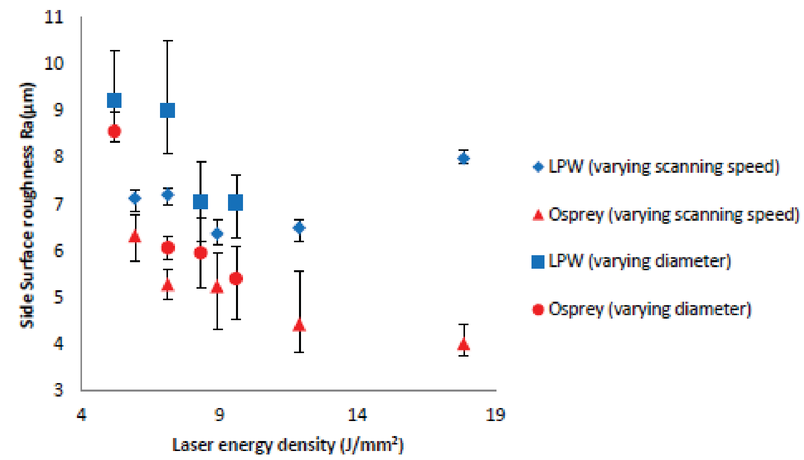

Figure.5 Side surface roughness for both SO and LPW parts

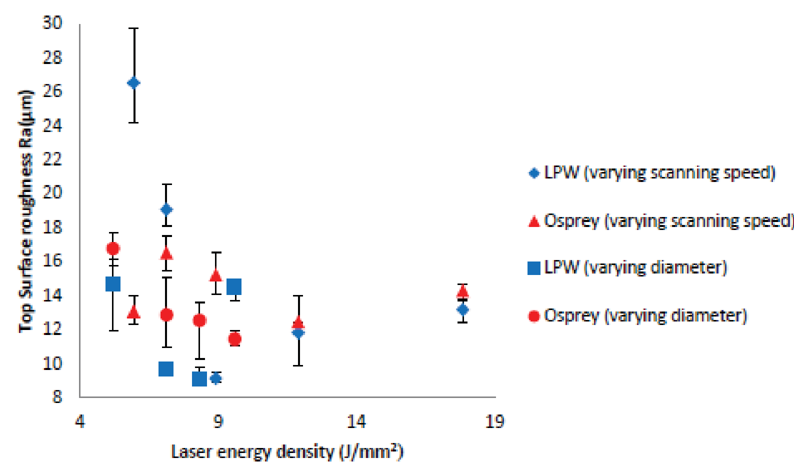

Figure.6 Top surface roughness for both SO and LPW parts

Known surface finish issue

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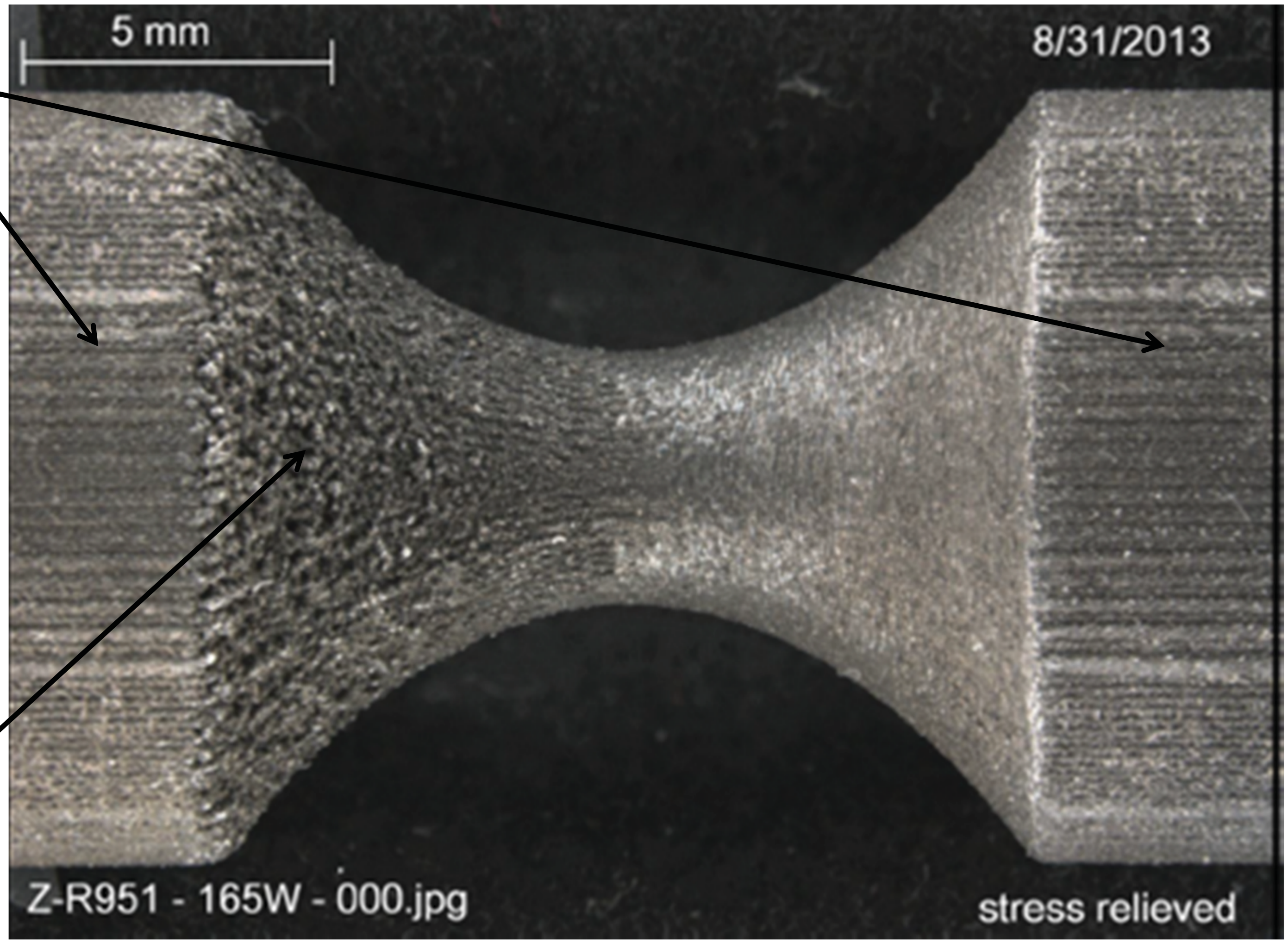
Short tensile bar

Patterned surface roughness on cylindrical vertical surfaces



Other nasty surface caused by overhang (not the topic of this study)

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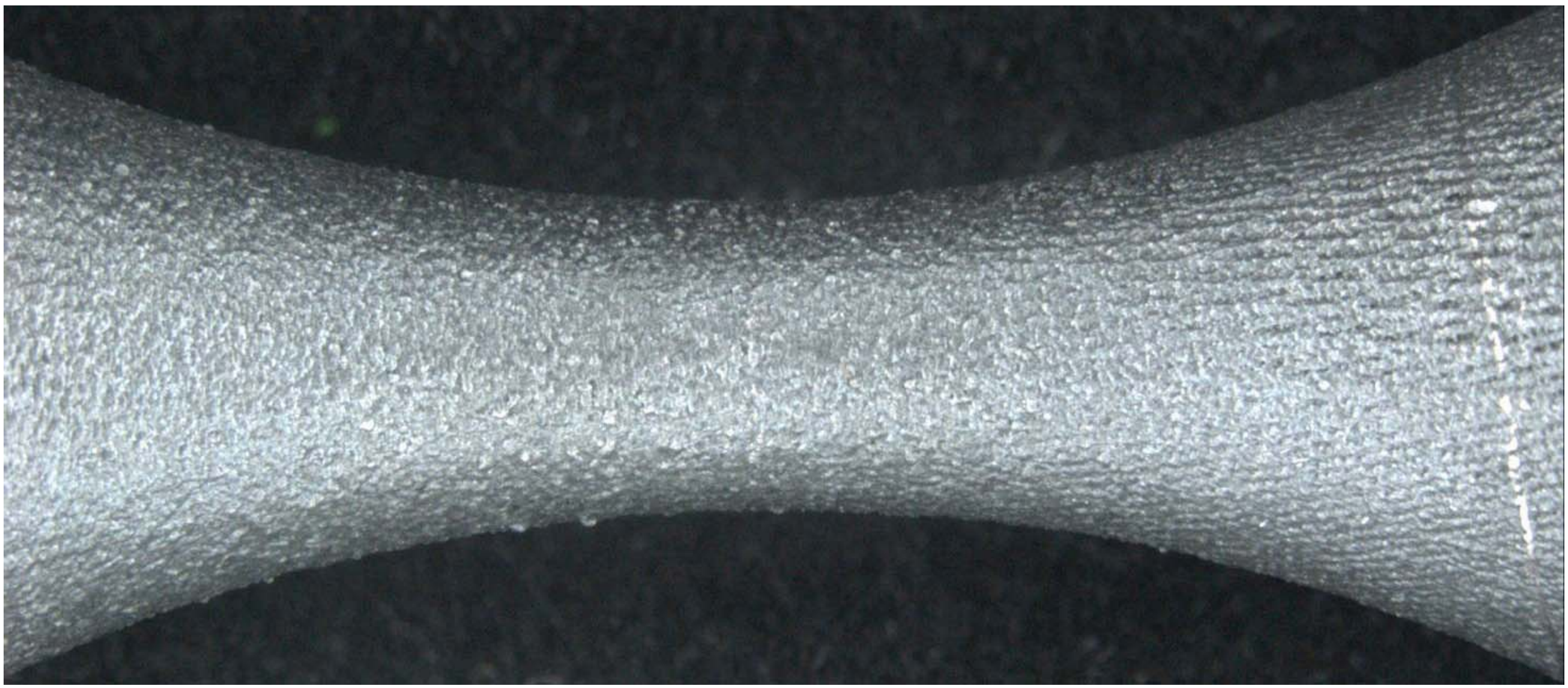
Tensile bar gauge section

Patterned surface texture on this end only



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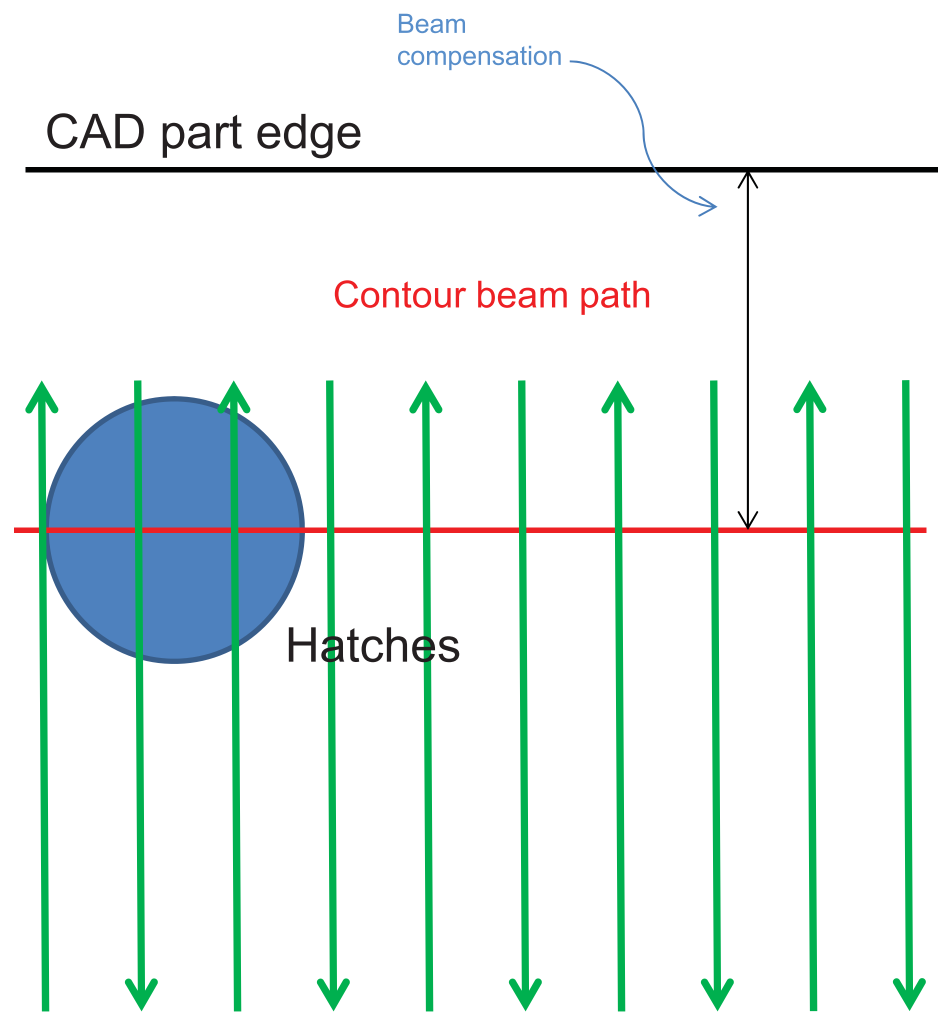
Hypothesis for cause of patterned surface roughness

- Beam compensation value set too high
- Causes hatches to penetrate contour
- Effect more prominent on surfaces that are downfacing due to lack of remelting contour



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Contour Parameter Optimization DOE 1

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Goals

- Improve as-built surface finish
- Better understand relationship between contour scan L and surface finish
- Determine if patterned surface finish observed on tensile bars is a function of beam offset

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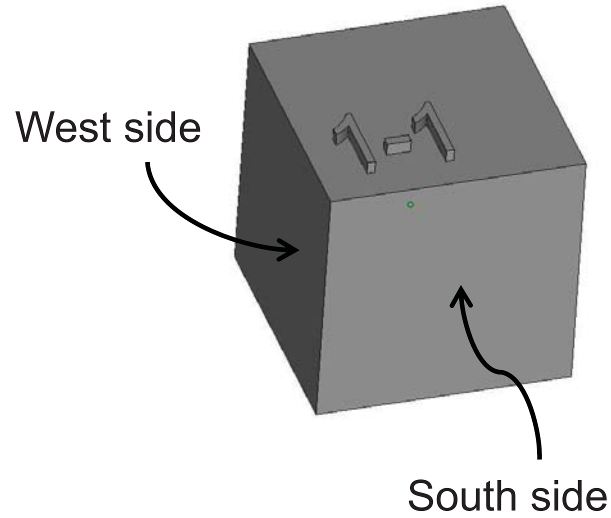
Method

- Build small (10x10x10 mm) cubes
  - Vary contour power (2 levels), speed (2 levels), and beam offset (3 levels)
  - Full factorial to make 12 parts, no replicates/repeats
- Measure surface roughness values on all 4 sidewalls
  - Orientation (N, E, S, W) indicated by location/orientation of numbers
  - Analyze for effects of speed and power
  - Use Ra as primary response, but record Rz and Rv
- Also observe each sample for patterned surface texture
  - Determine correlation between presence of pattern and beam compensation value



Part #	Contour Speed	Contour Power	Beam comp.
1-1	400	180	0.06
1-2	400	180	0.1
1-3	400	180	0.14
2-1	1600	180	0.06
2-2	1600	180	0.1
2-3	1600	180	0.14
3-1	400	100	0.06
3-2	400	100	0.1
3-3	400	100	0.14
4-1	1600	100	0.06
4-2	1600	100	0.1
4-3	1600	100	0.14

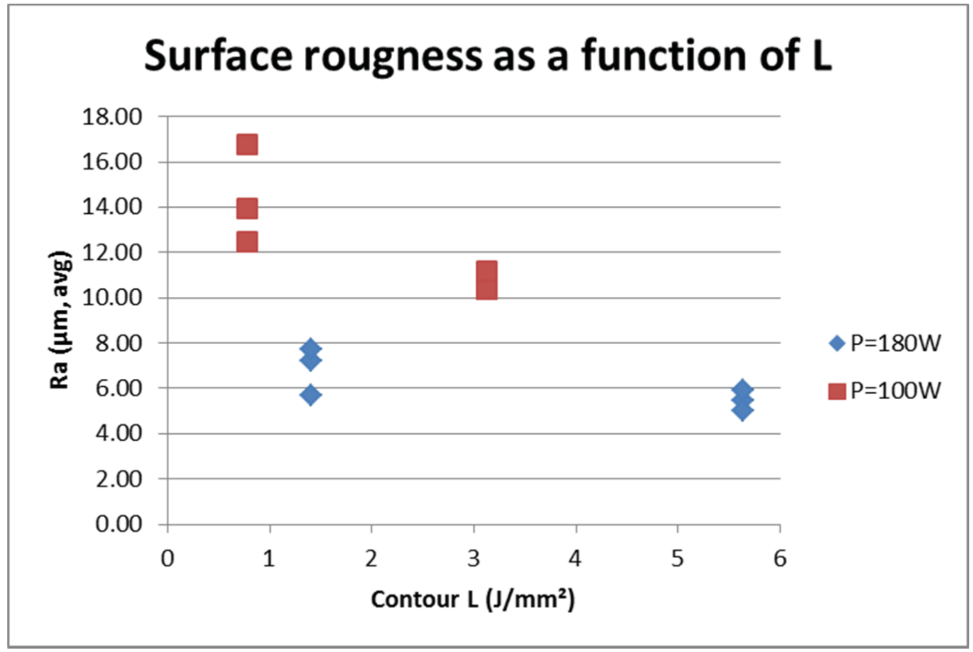
Results

- All Ra values in µm
  - Measured by Keyence VK-X100 at 10x
  - No filtering or noise elimination in determination of Ra value
  - To insure consistency, procedure template used
- Pattern determined by visual assesment
  - 0 for no pattern, 1 for visible vertical lines
- Local energy density L calculated assuming 80 µm beam

	Inside contour				North		East		South		West	
Sample#	Speed (mm/s)	Power (W)	Beam comp. (mm)	L (J/mm²)	Ra	Pattern?	Ra	Pattern?	Ra	Pattern?	Ra	Pattern?
1-1	400	180	0.06	5.63	5.023	0	4.454	0	5.087	0	7.205	0
1-2	400	180	0.1	5.63	4.85	0	4.576	0	5.142	0	5.471	0
1-3	400	180	0.14	5.63	6.121	0	5.374	0	6.339	0	5.783	0
2-1	1600	180	0.06	1.41	5.374	1	6.252	1	11.598	1	5.646	1
2-2	1600	180	0.1	1.41	4.945	1	4.337	1	7.952	1	5.454	0
2-3	1600	180	0.14	1.41	8.61	0	7.078	1	8.318	1	6.826	1
3-1	400	100	0.06	3.13	8.62	1	9.51	1	13.543	1	9.86	1
3-2	400	100	0.1	3.13	11	0	9.352	0	11.501	1	9.64	0
3-3	400	100	0.14	3.13	12.067	0	10.039	0	12.423	0	10.132	0
4-1	1600	100	0.06	0.78	11.642	1	15.113	1	12.371	1	10.838	1
4-2	1600	100	0.1	0.78	17.912	1	12.061	1	13.297	1	12.425	1
4-3	1600	100	0.14	0.78	22.628	1	15.32	1	13.447	1	15.569	1

Surface roughness as a function of L

- Surface roughness decreases with increasing contour energy
- High laser power appears beneficial over low power
- Highest energy parts (1-1 to 1-3) are shiny
  - Need to section to insure no porosity induced



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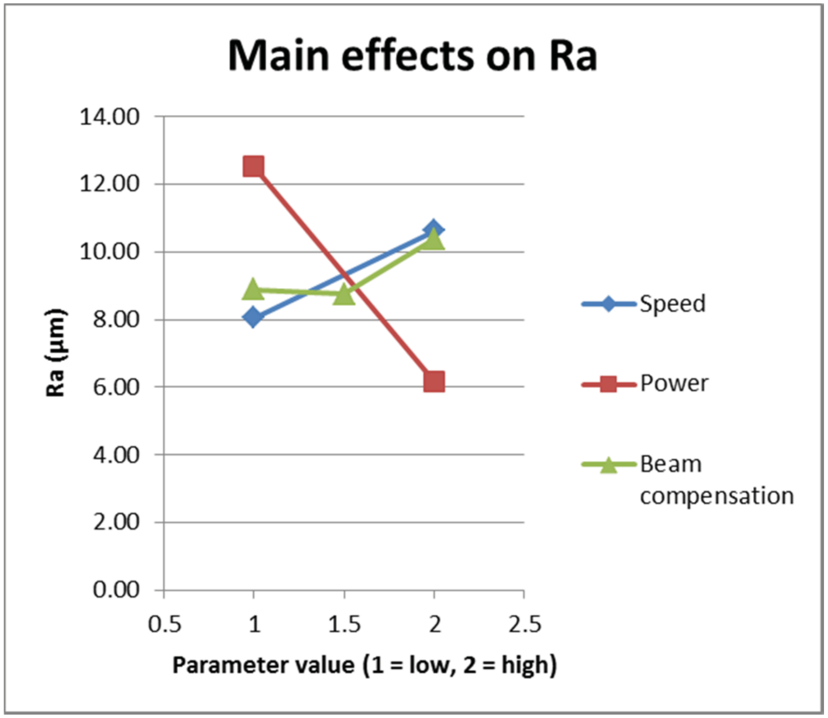
Main effects of basic parameters on Ra

- Again, higher power shows up as dominant parameter
  - High power = good
- Speed also effective
  - Lower speed = good
- Beam compensation somewhat more complicated
  - Lowest Ra average occurs at middle value



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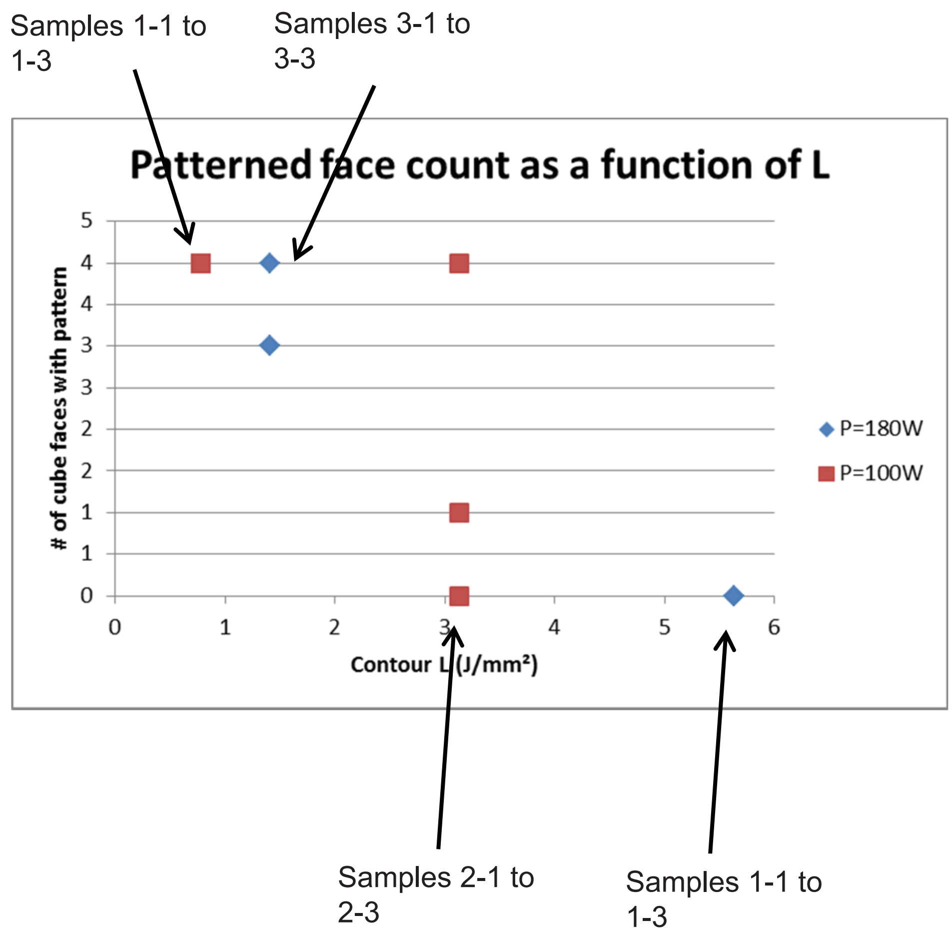
Patterning as a function of L

- Patterning decreases with increasing energy
- Not a very fine measure, but some interesting effects in samples 2 and 3



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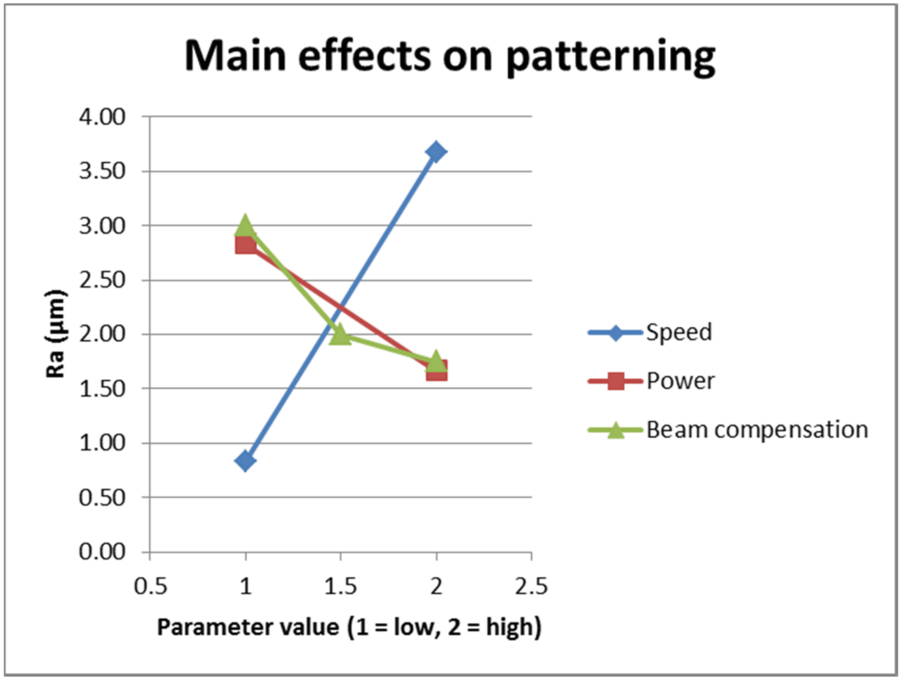
Main effects of basic parameters on patterning

- Speed and power both important
  - Could primarily be through contribution to L
- Beam compensation also important
  - High value appears beneficial???



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Patterning in part group 2

- Beam compensation different for each part
  - To recap, beam compensation pulls contour back from CAD edge of part to compensate for beam width
- Pattern appears strongest in part 2-1 w/ beam comp 0.06
- Decreasing in 2-2 w/ beam comp 0.1
- Not present in 2-3 w/ beam comp 0.14
- Set backwards or implemented in strange fashion by CL???

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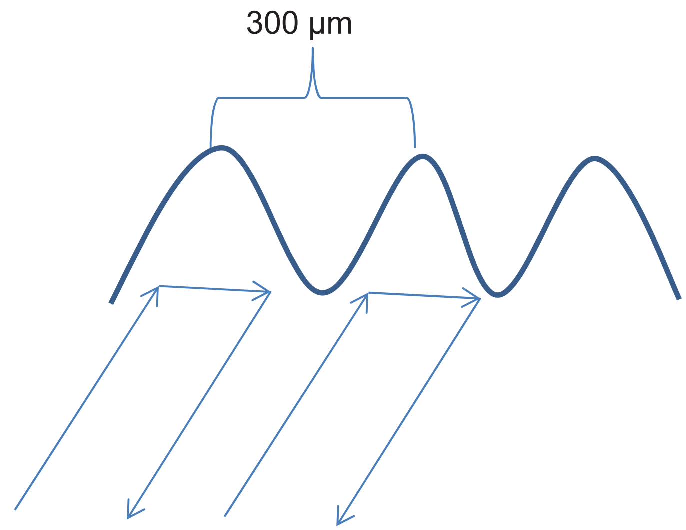
Review of Predictions

- ✓ Higher local energy L will lead to lower Ra
- ✗ Patterning will be prominent on samples with high beam comp. (1-3, 2-3, 3-3, 4-3)
  - Opposite observed
- ✓ Patterning will be less prominent on higher contour scan energy

Further insight

Photograph of 2-1

- "Wavelength" of surface defects also observed with Keyence scans
  - ~300 μm
  - Confirmed by inspection of photos (part 10 mm wide, 33-34 stripes)
- Hatch spacing 105 μm, but oriented at 45° to walls
  - Spacing between individual hatches should be 105*√2 ≈150 μm
  - Waviness consistent with a distance of 2 hatch spacings
  - Pattern likely due to "meander" setting in hatch scan algorithm
    - Produces heat concentrations at ends of scan vectors
  - Could be problematic by producing subcontour porosity



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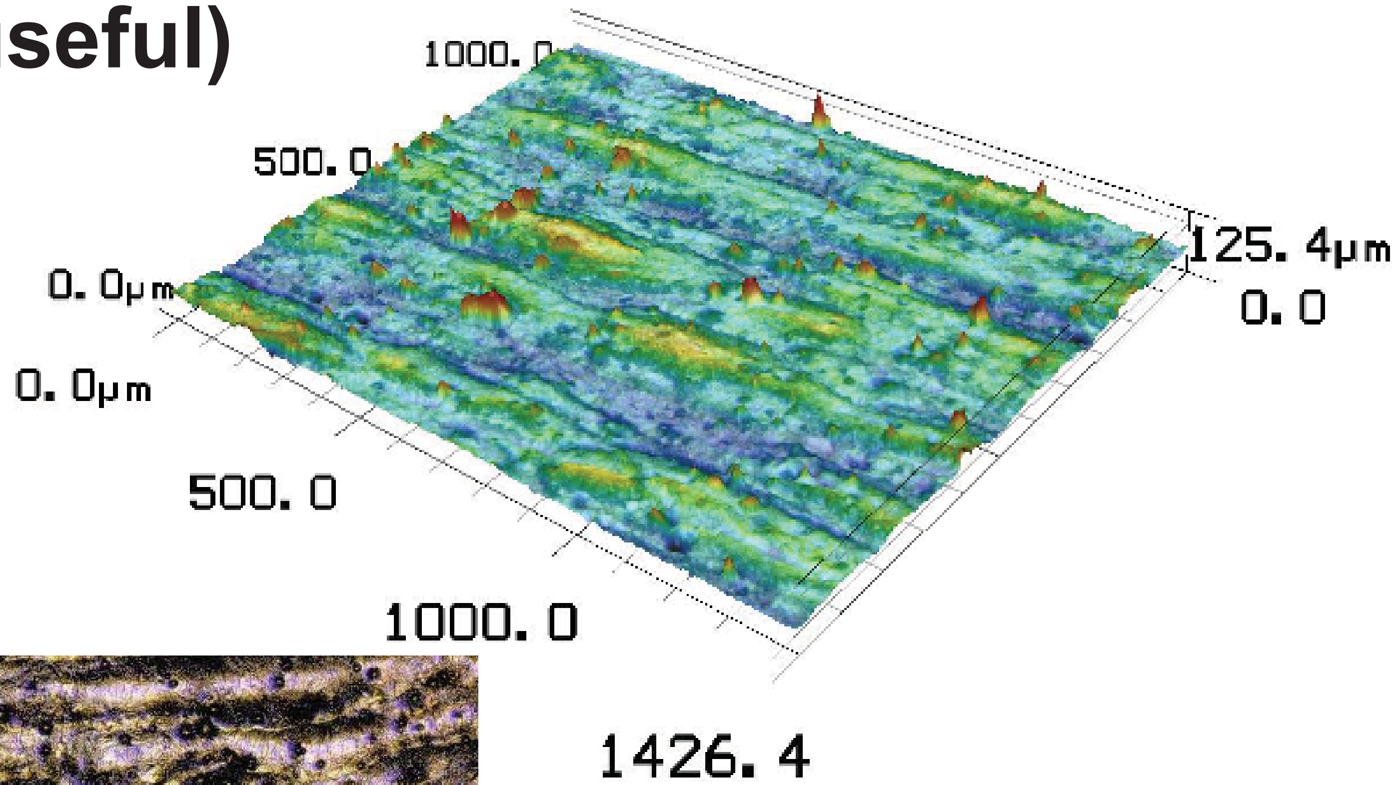
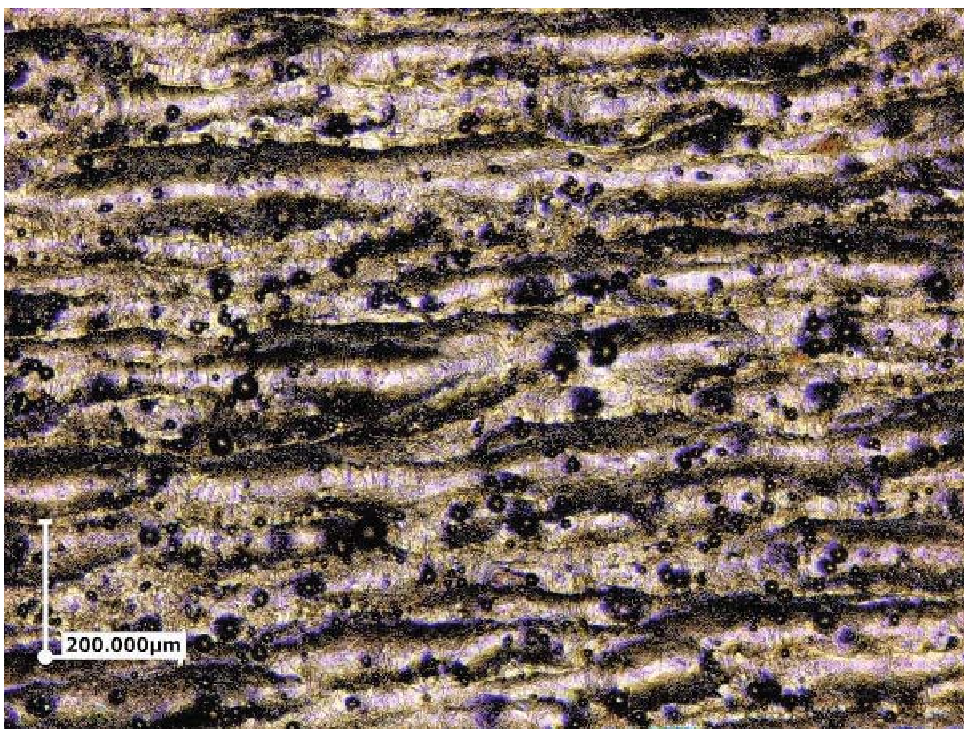
Cool (and useful) pictures



Sample 1-1
North face
Ra = 5 µm



Build Direction

Surface roughness primarily associated with small attached powder particles and layerwise waviness

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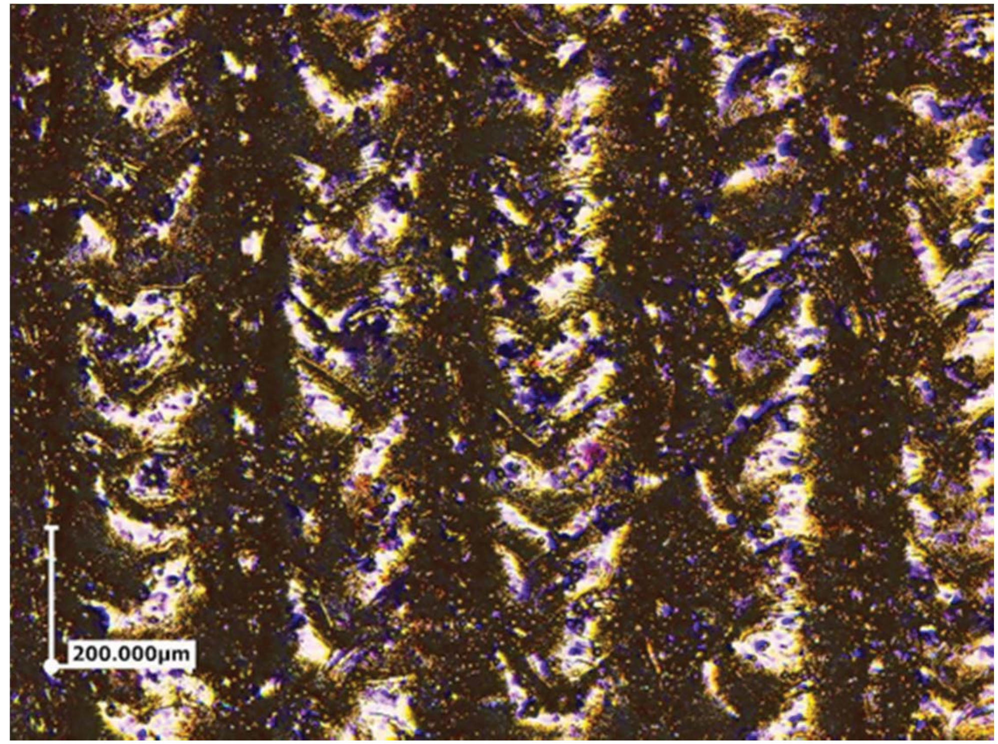
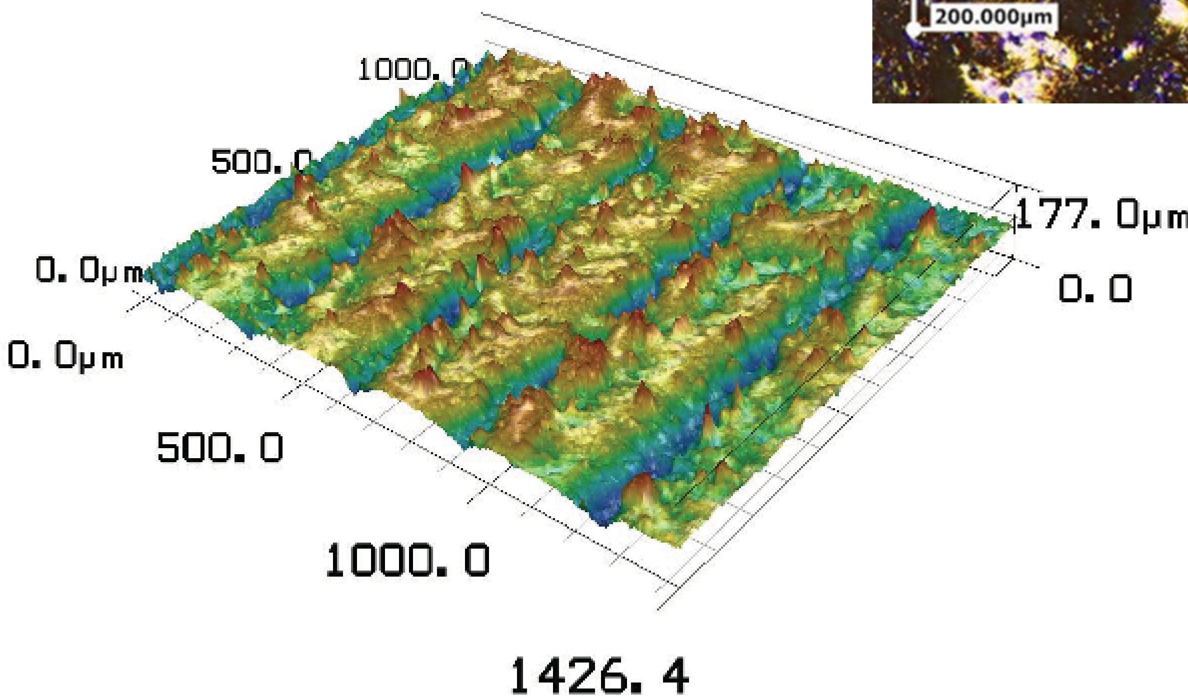
Not as good

Sample 2-1
South face
Ra = 11.5 μm

Build Direction





Surface roughness primarily associated with small attached powder particles and substantial vertical waviness

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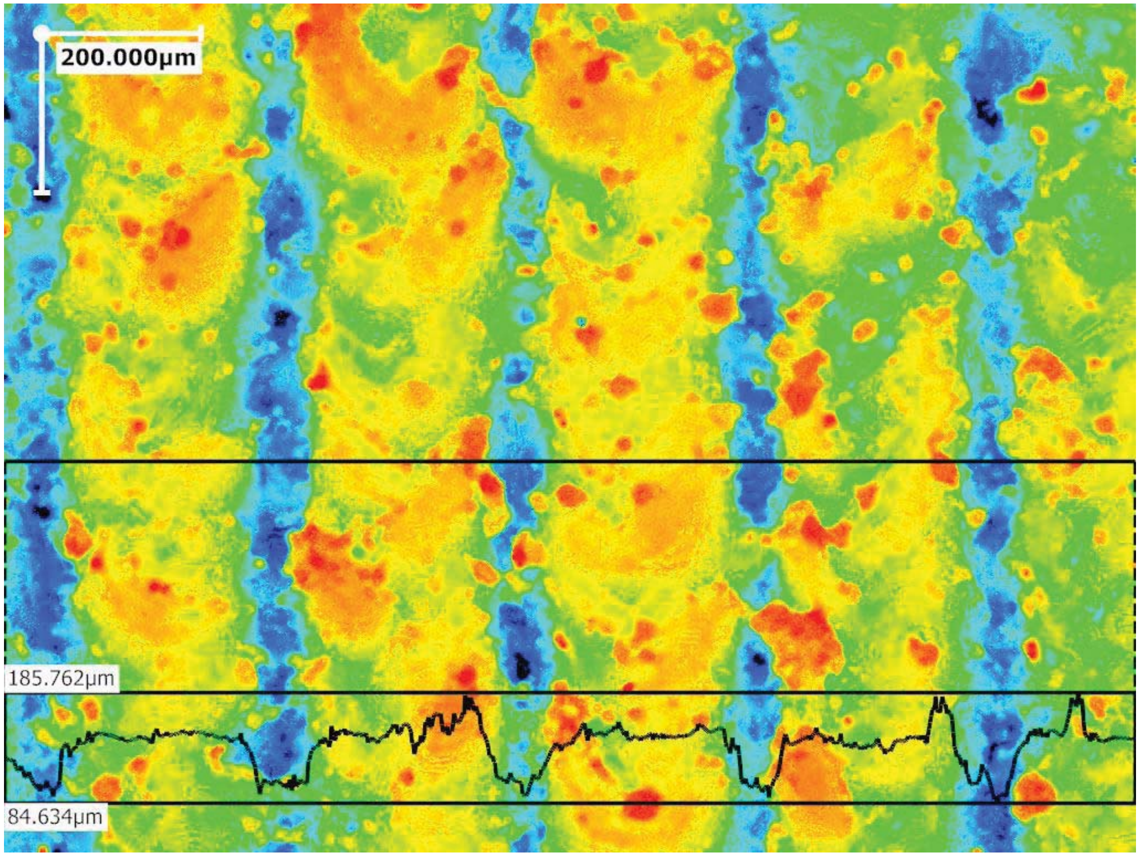
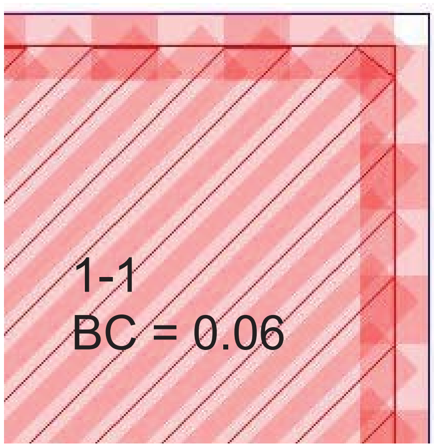
2-1 South face height pattern

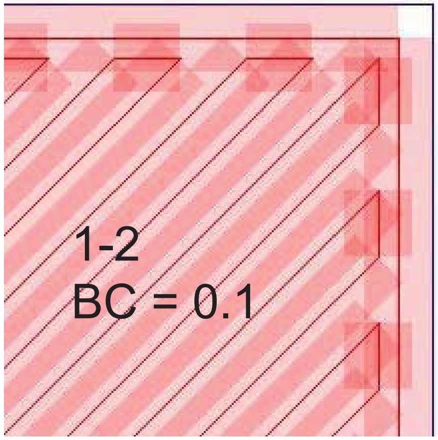


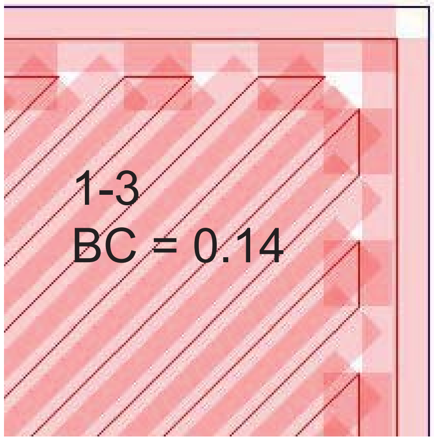
Clear periodicity of about 300 µm, amplitude somewhere around 50-75 µm

Explanation of confusing beam compensation results

- Pictures show scan paths in corner of cubes
  - Blue is CAD contour
  - Red lines are scan lines
  - Contour is first in from CAD contour
  - Hatches inside contours
- Beam compensation applies to HATCH scans, not contours
  - Contour offsets also available in Magics
  - There are additional effects with CL machine parameters
    - A2 and A3?
- Explains observed effects

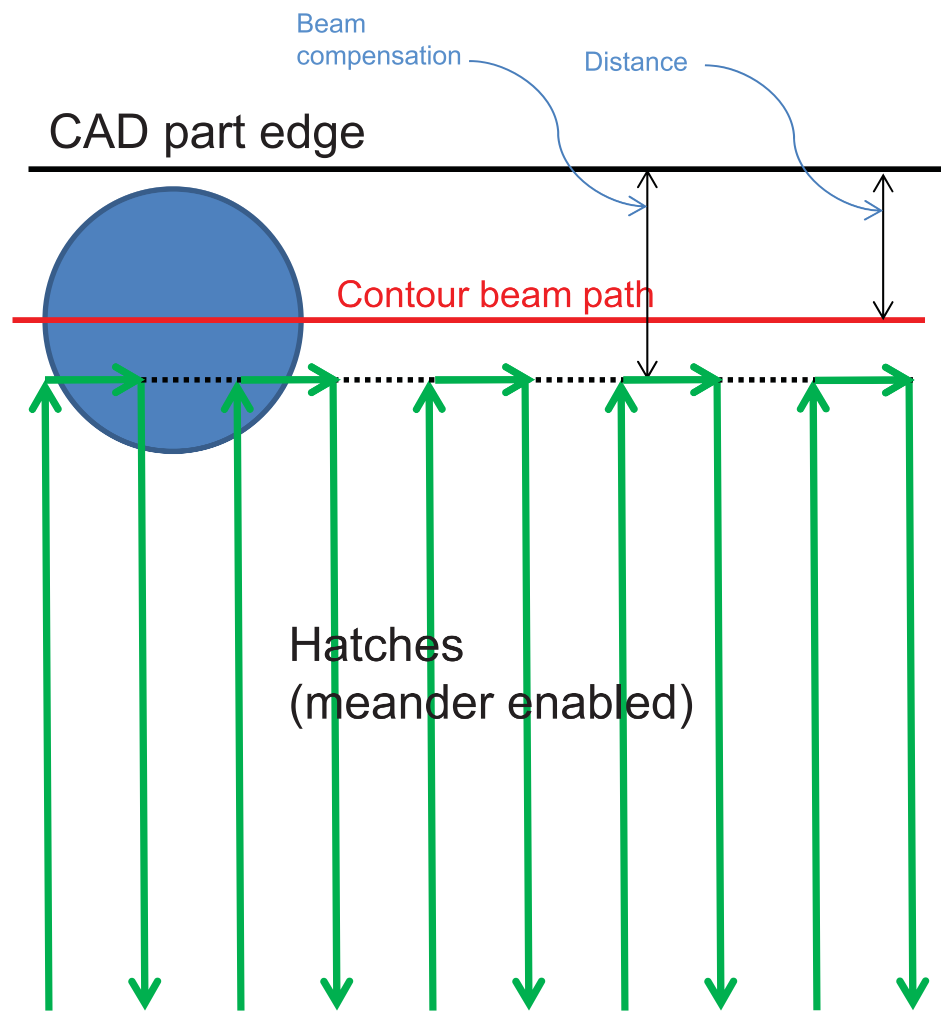






Beam compensation revised

- An attempt to insure parts are not oversize by compensating for width of contour melt pool
  - Analogous to machine tool diameter in machining, kerf width in sawing
- Can be adjusted in software on a per-part basis



Next steps

- Determination of method to eliminate waviness
  – Build parts with hatch scan only (no contours!)
  – Evaluate default 45 µm parameters as compared to custom parameters
- Produce documentation for the effects of scan parameters
  – Magics parameters Beam Compensation, Distance
  – Concept Laser Software parameters Trace Width, A1, A2, A3 in Continuous scanning context

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