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Investigating Surface Roughness effects on Emissivity for Metal Additive Parts

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Background

Non Contact Thermal Measurements in Additive Manufacturing

- Thermography measurements are highly popular in the research community for the monitoring of additive manufacturing processes
- Monitoring and control of thermal history of parts is key in quality assurance
- In thermal monitoring, the variable that has the greatest impact on measurements is emissivity
  - Emissivity is dependent on material composition, temperature, material phase, and surface roughness
- In metal AM monitoring there are four main ranges of thermography measurement
  - NIR (0.8-1.5), SWIR (1-3 microns), MWIR (3-5 microns), LWIR (8-13 microns)

Emissivity Dependence on Surface Roughness

- In literature, it has been stated that emissivity depends on surface roughness
- The key relationship is R_{rms}/λ (where λ is the measurement wavelength)
- This is used to define the conditions where the surface roughness may have a large effect on the emissivity of the part
  - If the roughness is much smaller compared to the wavelength that the emissivity is measured at, then the emissivity has little dependence on surface roughness
  - If the roughness is 20% to 100% of the measuring wavelength, then there is some dependence on surface roughness
  - If the roughness scale is greater than 100% of the wavelength, then there is a large dependence of emissivity on surface roughness

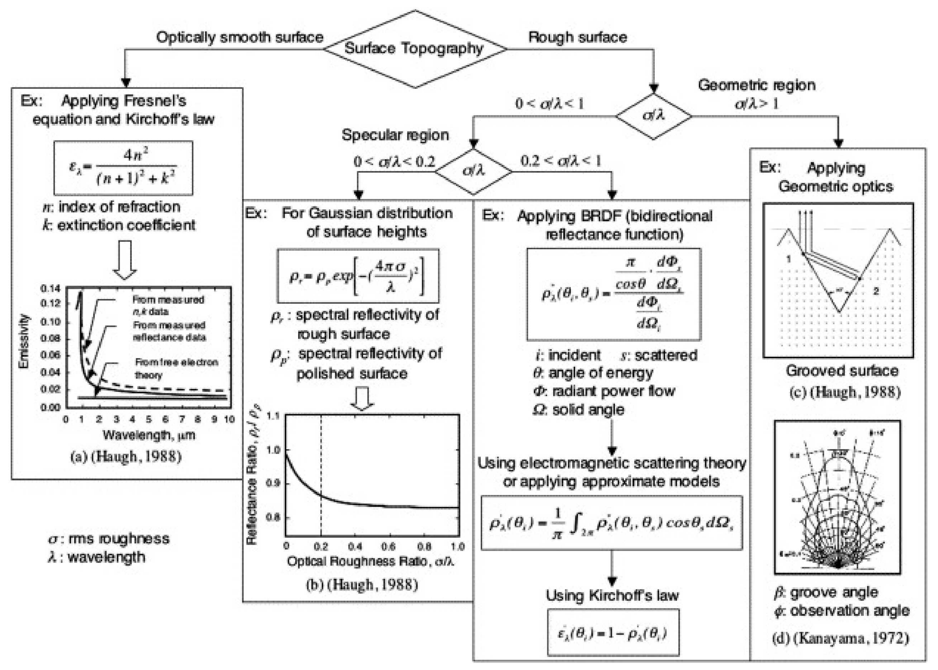


Diagram describe determination of emissivity based on surface roughness and measurement wavelength (Wen et al. 2006)

Experimental Goal

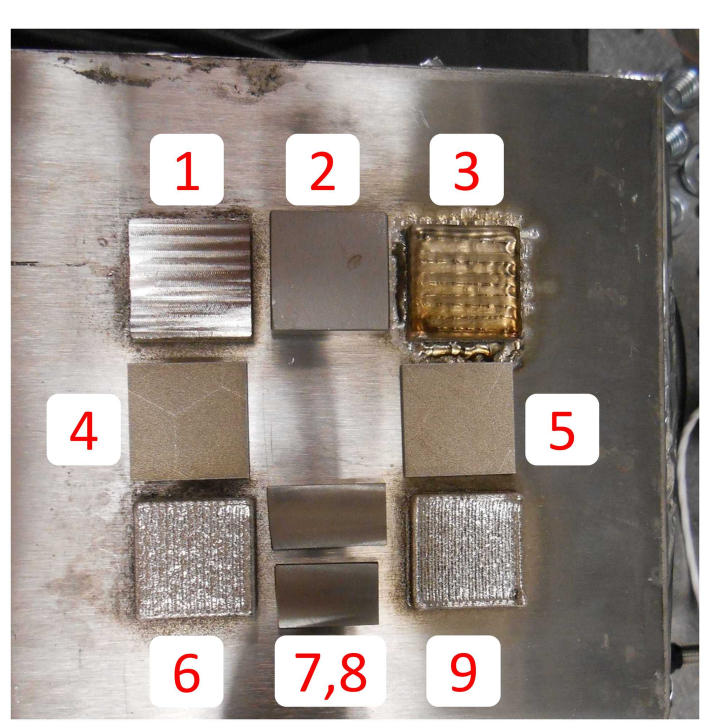
- To see if the surface roughness of metallic additively manufactured parts affects the emissivity
- To determine level of dependence emissivity has on various surface roughness parameters

Sample Information

Metal Additively Manufactured Samples

1. 304L Stainless Steel LENS milled surface
2. 316 Stainless Steel stock finish
3. 304L Stainless Steel LENS 'laser glazed' (laser was defocused and scan lines were repeated to create glazed surface)
4. 316 Stainless Steel DMLS
5. 316 Stainless Steel DMLS
6. 304L Stainless Steel LENS raw
7. 316 Stainless Steel DMLS milled surface
8. 316 Stainless Steel DMLS milled surface
9. 304L Stainless Steel LENS raw

- All samples were roughly 25x25 mm in area with the exception of samples 7 and 8
- Both DMLS and LENS parts were used for this experiment to provide a large range of surface roughness

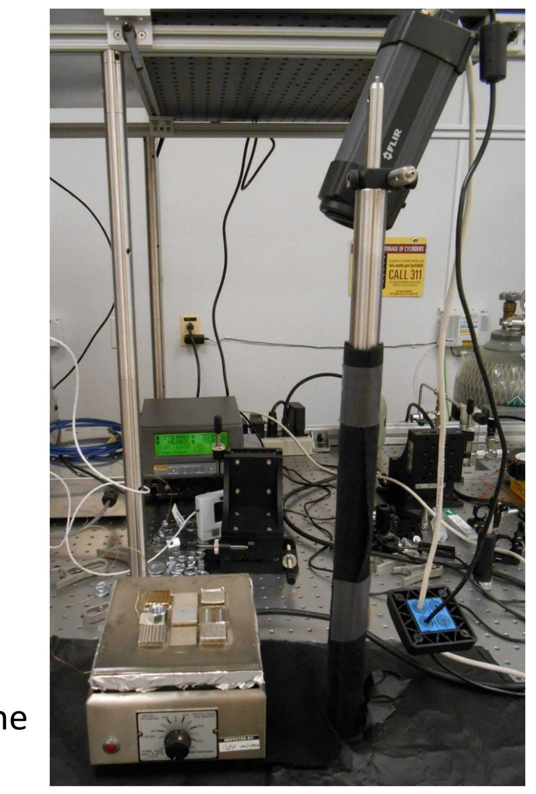


Visual Image of all nine samples on build plate from LENS process

Experimental Procedure

Experimental Setup

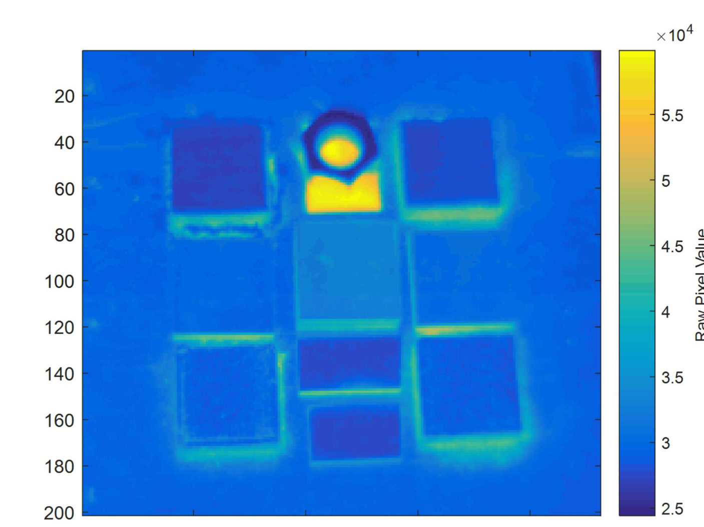
- FLIR Long-wave Infrared (LWIR) camera was used
  - Measures in the wavelength range of 8-13 microns
  - Camera is at 25 degree viewing angle
  - LWIR camera placed at an angle so that heat from the hot plate does not heat the camera significantly
- All samples were placed on top of LENS build plate, which four out of nine samples were attached to at the time of experiment
- The LENS build plate was set on top of a hot plate



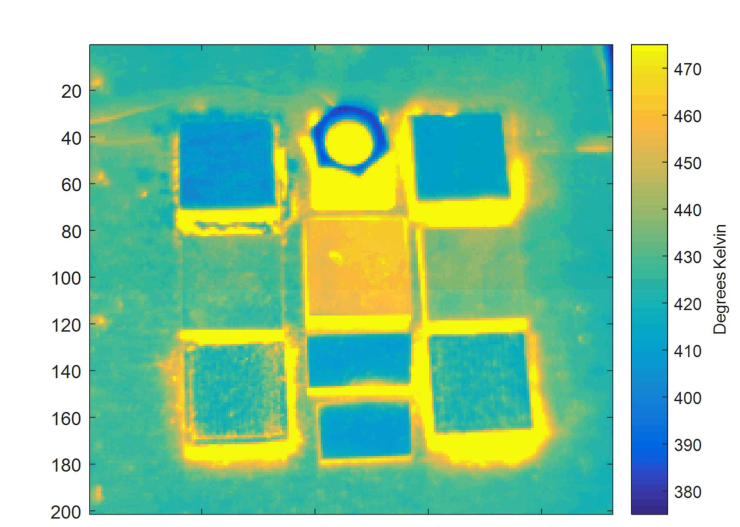
Experimental Setup

Experimental Procedure

- Contact thermocouple placed on LENS build plate to record temperature
- Blacked-out box placed over entire setup during experiment to reduce outside radiation from affecting the camera through direct radiation or reflection from specimens
- Hot plate heated to about 200 degrees Celsius and then set to cool down to about 100 Celsius while data sets gathered at every 10 degree temperature increment
- An additional data point was taken at room temperature
- Data gathered at each increment includes raw pixel thermal image, surface thermocouple value, camera input parameters, and timestamp



Raw Pixel Image of Samples from LWIR Camera



Thermal Image of Samples with Emissivity Value Input of .25

Roughness Measurements

- Surface roughness was measured by using a Keyence VR3100 3D measuring macroscope
- Measurements were taken with this method due to the extremely rough nature of some of the surfaces which can cause damage to contact profilometry instruments
- For each type of surface, at least five measurements were taken

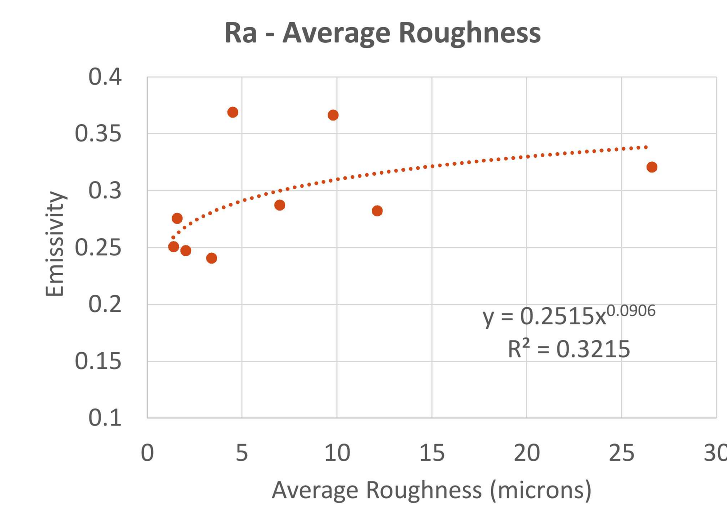
Average Surface Roughness Values

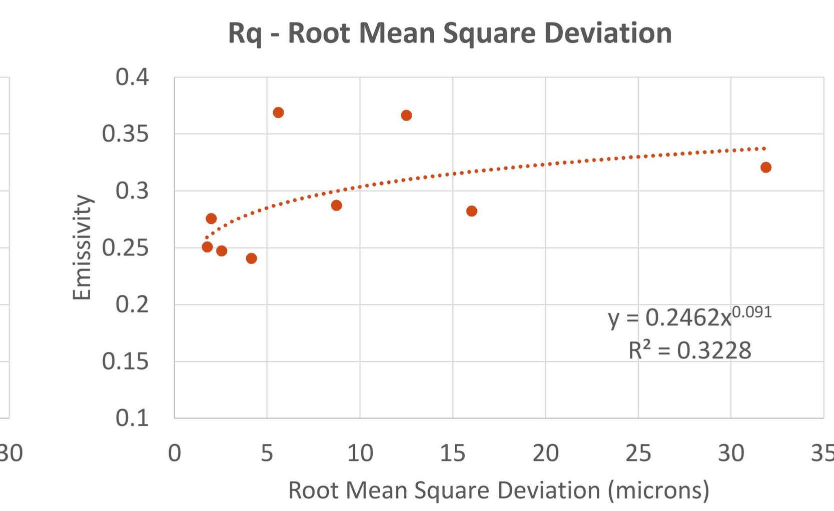
	LENS milled	LENS glazed	DMLS A	DMLS B	LENS A	DMLS Milled A	DMLS Milled B	LENS B	Stock Finish
Ra (μm)	3.39	2.02	6.97	9.79	26.59	1.57	1.38	12.12	4.49
Rq (μm)	4.13	2.53	8.72	12.50	31.88	1.97	1.75	16.02	5.60
Rsk	0.02	0.33	0.15	-0.21	0.47	0.28	0.19	0.70	-0.19
Rku	2.62	3.01	3.03	3.59	3.61	3.09	3.53	4.23	3.01
RΔq	0.43	0.23	0.59	0.96	1.46	0.15	0.16	0.86	0.56

Analysis Procedure

- The output of the camera as seen above is an image whose individual pixel values represent intensity of light gathered by the camera's sensor (also referred to as raw pixel image)
- This raw pixel image is then converted into an temperature image with a look up table that is generated using the camera input parameters such as transmission, atmospheric temperature, atmospheric humidity, object emissivity, etc.
- Each raw pixel image was gathered during the experiment at the same time the temperature of the plate was gathered
- Individual samples had a temperature offset due to uneven conduction through the plate; these were determined after the experiment using the surface thermocouple placed at each sample location
- An emissivity value for each sample at each temperature was found by minimizing the error of the actual temperature of the sample and the temperature determined by the object pixel image created using the look up tables in the entire range of possible emissivity values of 0 to 1.00 in .01 increments

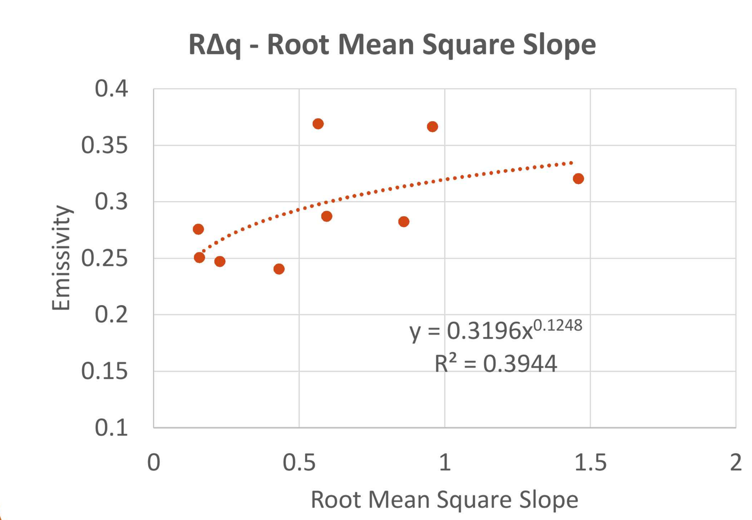
Results





Emissivity and Surface Roughness

- Ra and Rq had some of the best correlations with emissivity changes, but were poor predictors for accurately describing emissivity changes
- Due to the range of roughnesses of the samples, which places different samples in different optical regions as described in the diagram in the background section, the exact relationship between emissivity and surface roughness cannot be determined
- The general trend found was that the smoother surfaces have a lower emissivity, which is consistent with findings found in literature that rougher surfaces have higher emissivity than the smoother surfaces of same material composition
- The difference in emissivity between the samples remains relatively consistent as temperature is varied
- At a given temperature, the sample roughness range of 2-26 microns resulted in emissivity range of .15
- For the experiment, errors in sample temperature measurements with the incorrect emissivity value reached up to 25-30 degrees C in magnitude



Emissivity and Slope

- RΔq had the best fit trendline
- Literature has suggested that the slope of the peaks and valleys that make up the surface has an effect on the emissivity of the surface and is a better measure of emissivity changes than pure height measurements like Ra
- RΔq better describes the shape of the surface, but is still insufficient in fully describing emissivity changes

Conclusions

Overall Conclusions

- Emissivity does have a dependence on surface roughness
- Rougher surfaces have higher emissivity values
- Traditional surface roughness parameters are insufficient in describing emissivity changes
- The change in emissivity between samples is sufficient to generate significant thermal errors that could reduce quality of the parts produced during the process

Future Work

- Determine a surface parameter or characteristic that has a stronger correlation to changes in emissivity
- Investigate the range of that surface parameter generated by certain metal additive processes to determine the possible ranges of emissivity that can be seen

Acknowledgements

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