Is there a relationship between product shape complexity and process energy consumption in Electron Beam Melting?

Martin Baumers
Agenda

- Introduction
  - About the presenter
  - Context / Life Cycle Analysis
  - Electron Beam Melting (EBM)
  - Research question

- Methodology
  - Measuring product shape complexity
    - A 2D measure of convexity
  - A test part with a systematic variation
  - Energy consumption measurement

- Results
  - Energy consumption results
  - Correlation coefficients

- Context and conclusion

- Questions / discussion
Member of the Additive Manufacturing and 3D Printing Research Group (3DPRG) at Nottingham University

3DPRG activities cover various aspects of Additive Manufacturing technology
- Processes
- Materials
- Design systems

Host to the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing (in collaboration with Loughborough)
Context: Life Cycle Analysis

- To understand performance/impact of a durable good throughout its life cycle

- Can have varying objectives:
  - In consumer (or user) utility-related research: making statements on cumulative net benefit (which is a private incentive)
  - In sustainability focussed research: statements on cumulative environmental footprint (which is arises to society)

- Usually modelled in terms of a sequence of discrete stages (typically 5-6), for example PAS 2050:
  - Raw material generation
  - Manufacturing
  - Distribution
  - Use-phase
  - End-of-life
Context: Life Cycle Analysis

- Useful for process selection decisions in engineering:
  - Typically choosing a material/design/process combination
  - Supply chain configuration

- Optimization problem:
  - Maximization of private gain
  - Minimization of social cost
    - or some combination of both

- Requiring measurement of each stage
  - Normally based on empirical data

- Analysis of how variables/decisions impact stages, often leading to trade-offs
  - e.g. manufacturing energy consumption vs. use-phase efficiency
Research question

- It has been suggested that AM allows the manufacture of more complex product geometry at no additional ("marginal") cost (Hague et al., 2003)

- This research is about testing if such a statement holds for energy consumption
  - Only looking at the manufacturing stage
  - Other environmental impact are ignored

→ If true, AM may allow the creation of additional part functionality at zero extra energy cost
→ Potentially enabling very efficient and complex products
→ Interesting consequences for LCA
Electron Beam Melting (EBM)

- Variant of AM
- Schematic of EBM platforms:
Methodology used

- To address the research question experimentally, such product complexity needs to be defined.

- Product shape complexity is viewed as a subjective attribute and not a quantifiable property.

- Measurement of a property that is associated with complexity and is quantifiable:
  - Degree of convexity
  - Specifically: convexity of a perimeter
First step: implementation of a measurement tool

- Discretised measurement algorithm
- Bitmap-based implementation
- Inspired by radar
- Records what proportion of the perimeter is visible from each of ‘n’ loci
- Calculates a “Mean Connectivity Value” (MCV):

\[ MCV_i = \frac{\sum_{n=1}^{n} CV_n}{n} \]
Second step: test part design

- Experimental analysis of the effect of complexity on resource consumption
- Design of test specimen
  - Opportunity to mirror layer-by-layer process of AM
  - Retain existing approach to measure complexity in 2D
  - Measurement of a sequence of shapes

![Diagram of test part design with dimensions: Z-height: 24 mm, 75 mm side lengths]
Test part design
Third step: Energy consumption measurement

- **Yokogawa CW240 Clamp-on power meter**
  - Logs data on 137 electricity related variables
  - Variable measurement cycle (from 50 Hz)
  - Various possible wiring configurations

Voltage probes in contact with phases and neutral

Yokogawa CW240

Current clamps on phases and neutral
Energy consumption results

![Graph showing energy consumption per layer (kJ) vs. layer number.

- Layer preparation
- Layer pre-heating
- Melting

The graph illustrates the energy consumption pattern across different layers, with distinct phases for layer preparation, layer pre-heating, and melting.]
Correlation coefficients

- Calculation of standard Pearson (product moment) correlation coefficients is used to assess the research question:

\[ \rho_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} \]

- Describes the degree of linear association between two variables

- Results

\[ \rho_{\text{Perimeter,Layer Energy}} = 0.6568 \]
\[ \rho_{\text{Area,Layer Energy}} = 0.8263 \]
\[ \rho_{\text{MCV,Layer Energy}} = -0.3544 \]

The negative sign is due to the specification of MCV.
Manufacturing context

- Can be contrasted neatly with patterns of energy consumption observed for CNC machining:

Morrow et al., 2007
Interpretation

- Result indicates a disconnect:
  - Between process energy consumption and specifics of geometry
  - Some design decisions regarding the use-phase may no longer affect the manufacturing stage

Example: adding a geometric feature

- No additional manufacturing cost (e.g. unlike machining)
- Reduced weight, better efficiency

→ i.e. cost minimisation during manufacturing may no longer have an adverse effect on environmental use-phase performance
Interpretation

- For EBM, process energy consumption appears largely volume driven.

- In many applications, light weight is an important performance dimension (e.g. aerospace).

- Manufacturing cost in AM is also largely determined by deposited volume.

  \(\rightarrow\) Private incentive to minimize manufacturing cost aligns nicely with requirement to minimise use-phase energy consumption.
Conclusions

- This research has performed a quantitative assessment of attributes associated with product shape complexity.

- Thus, weak correlation ($\rho = 0.35$) provides evidence that energy consumption in EBM is not driven by complexity.

- The same argument of free marginal complexity made for the financial cost of AM can be repeated for energy consumption of EBM.
Conclusions… leading to more questions!

- Results support the idea that new digital (manufacturing) technologies can align private incentives and societal needs
  - This reflects the idea of achieving “Negawatts” for a low energy path (Lovins)

- Conventionally, the role of balancing private and social interests is assigned to the policymaker
  - E.g. issuing carbon permits, taxing pollution, etc.

- For manufacturing processes, the evidence from AM suggests that it may possible to collapse both aspects in some areas of technological innovation
  - Would this be superior to regulating a conventional manufacturing industry?
  - Which position should the policymaker take?
Thank You!

Martin Baumers  
Research Fellow  
3D Printing Research Group (3DPRG)  
University of Nottingham  
Tel: +44 (0) 115 951 3877  
Martin.baumers@nottingham.ac.uk