Title

Quantifying the Improvements in Rapid Prototyping and Product Life Cycle Performance Created by Machining

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Quantifying the Improvements in Rapid Prototyping and Product Life Cycle Performance Created by Machining

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Abstract

This paper describes three projects that utilized machining for advanced manufacturing technology. The first project compared micromilling to laser ablation and 3D printing for rapid prototyping microfluidic devices. While micromilling created features with better accuracy, precision, and quality relative to other alternatives, it required longer processing time and still needs further development to displace existing prototyping methods. The second project developed an environmental value stream mapping approach for SMEs that highlights processes with high impact and evaluates potential improvements for these processes. This approach reduced energy consumption by 18% in a stainless steel blind flange process chain. The last project explores the impact of manufacturing decisions on the product life cycle so that decision-makers may leverage these relationships for life cycle optimization. Each of these projects shows how traditional manufacturing, such as machining, can be used in new ways to improve manufacturing.

Keywords: Machining, Laser ablation, 3D printing, Microfluidics, Value stream mapping, Leveraging

1 INTRODUCTION

Advanced manufacturing technologies improve processes and enable an idea to progress quickly from research and development to a finished product [1]. These technologies could be in emerging areas (e.g., information technology, nanotechnology, or biotechnology) or they could be as simple as using existing manufacturing technology in new ways (e.g., 3D printing to create products beyond prototypes). Ultimately, advanced manufacturing allows manufacturers to effectively and efficiently respond to new demands and limitations placed on them by customers, markets, suppliers, and governments.

This paper will explore three studies that utilized machining to develop advanced manufacturing technology. In the first study, micromilling was compared to other rapid prototyping techniques for microfluidic applications. Each processing alternative presents a potential improvement on existing approaches by enabling a more efficient, cost-effective means to create complex geometries at a variety of scales and in a variety of materials. The next two studies addressed the need for tools that improve the environmental sustainability of manufacturing. First, we will discuss the development of a product-centered environmental value stream mapping tool for decision-making in small- and medium-sized enterprises (SMEs). Then, we will extend this discussion to the product life cycle by describing on-going research developing tools that enable manufacturers to leverage their processes for life cycle optimization.

2 COMPARISON OF RAPID PROTOTYPING TECHNIQUES FOR MICROFLUIDIC APPLICATIONS

Microfluidics have become increasingly popular for many applications from biodefense to molecular biology [2,3]. These devices are primarily made using photolithography, which refers to processes that use light to define features in a thin layer (<300 μm) of polymer coated on silicon wafers. However, photolithography is unable to create various three dimensional geometries in different materials and at a variety of scales in an efficient and cost-effective manner [3]. Thus, the continued advancement of microfluidics requires the development of faster, more precise manufacturing methods for both prototyping and production. This research explored the feasibility of three alternatives to photolithography for rapid prototyping: micromilling, laser ablation, and 3D printing.

2.1 Experimental Methodology

A test part (see Figure 1) was developed to compare the fabrication time, accuracy and precision, and part quality of the three rapid prototyping techniques explored in this study. This part was designed with several key features commonly found in microfluidic devices, including channel arrays, intersecting channels, round pegs, and flat planes.

2.1.1 Micromilling

The microfluidic test part was machined from 20x20x6.35 mm cast acrylic stock on a Mori Seiki NVD1500. The part was placed on parallels that had a spring placed between them to improve fixturing stiffness. The part reference and tool heights were found by moving the tool towards the part in increments of 1 μm until a chip was observed using a magnifying glass.

The machining process used three uncoated solid carbide 2-flute endmills from Accupro. The spindle speed for each endmill was determined based on the manufacturer's specification and is shown in Table 1; the feed rates were an order of magnitude lower than the manufacturer's specification to ensure that the smaller features in the test part were resolved [4]. The width of cut was 100% and 50% of the tool diameter for slotting and facing, respectively. All cuts were made at full depth of cut for each feature, and only air cooling was used.

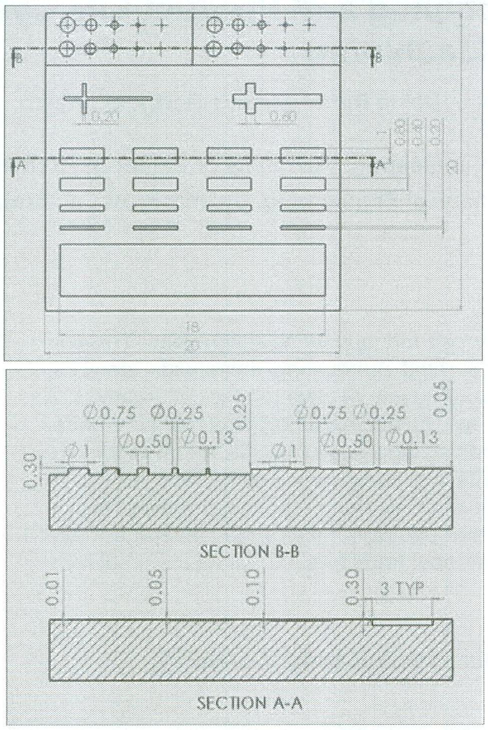

Figure 1: Dimensioned drawings of microfluidic test part.

Table 1: Processing parameters for micromilling (after [4]).

Tool Diameter (mm)	Spindle Speed (RPM)	Feed Rate (mm/min)
1	30000	80
0.4	40000	45
0.2	40000	22

2.1.2 Laser Ablation

A Universal Laser Systems PLS6MW platform was used to create the microfluidic test part from the same cast acrylic stock material processed by micromilling. This equipment uses a 10.6 µm wavelength CO_2 laser that can etch a range of materials including plastics, textiles, wood, and some metals [5]. While the accuracy and precision of the laser is not well characterized, it is much more accurate in the z-direction. The depth of etch in the z-direction is determined by the speed, power, and pulse modulation of the laser; this relationship must be characterized for each material by the end-user. The relationship was empirically defined in this study by setting the pulse modulation to 1000 PPI and varying speed and power and measuring the subsequent depth of cut using a surface profilometer (see Section 2.1.4 for more details).

2.1.3 3D Printing

An Object Connex350 3D printing system was used to create the microfluidic test part using VeroClear RGD810 material, which simulates transparent thermoplastics. This 3D printing system uses an inkjet-style printer head to deposit droplets of UV-curing liquid polymer with a resolution of 600 dpi along the x- and y-axes and 1600 dpi along the z-axis and minimum wall thickness of 0.6 mm [6]. To improve surface quality, a "glossy" finish was selected and the part was oriented such that the thickness of the finished test part was in the z-direction.

2.1.4 Metrology Tools

Accuracy and precision were evaluated by focusing on the channel width, channel depth, and peg roundness. The channel width and peg roundness were measured using a Keyence VHX-500F optical microscope with proprietary analysis software. The microscope's 2.11 MP CCD measures over a 1628x1236 pixel area with a resolution determined by the magnification of the microscope; most measurements were made at 100x magnification, which corresponded to a resolution of 600 nm. The built-in "parallel" and "circle" utilities were used to measure the width and roundness, respectively. Both utilities measure distance based on pixel size and user-defined features. An Alpha Step IQ (ASIQ) surface profilometer was used to measure the channel depth. The ASIQ utilizes a stylus tip with a 6 µm tip diameter and 60° taper. It has a maximum step height of 750 µm, maximum scan height of 2 mm, and a resolution of 12 nm.

Part quality was primarily described by the surface roughness on the bottom surface of the channels, which is an important consideration for microfluidic devices since rough channels slow fluid flow and rough surfaces inhibit bonding. The ASIQ surface profilometer was used without a filter to measure the roughness of the channels in the parallel and perpendicular direction to feed. Finally, part quality was also qualitatively described using images from a Hitachi S-2460N variable vacuum scanning electron microscope (SEM). This SEM has a 4 nm resolution at high vacuum and 41 magnification steps from 20x to 200000x. To use the SEM, each test part that was measured was first coated with a 150 Å thick layer of gold.

2.2 Experimental Results

The process time is an important metric for any rapid prototyping method. Two measures of process time were estimated based on the toolpath used to create the test parts. The first metric is the time to first prototype, which is the time needed to develop a part once a CAD model has been created and includes setup and fixturing. The second metric is the time to subsequent prototype, which is the time needed to make a second part that has a minor change from the first. Table 2 shows both metrics for each of the three prototyping alternatives.

Table 2: Estimated process time to create a prototype.

Fabrication Method	First Prototype	Subsequent Prototype
Micromilling	8 h	2 h
Laser Ablation	4 h	10 min
3D Printing	30 min	30 min

The measured accuracy and precision of the channel width were defined as the average and standard deviation of the measured percent error for four channels, respectively. Specifically, this study focused on the two narrowest sets of channels in the test part, each group of which had a nominal width of 200 µm and 400 µm and a nominal depth that varied from 10 µm to 300 µm. Table 3 summarizes the measured accuracy and precision of the channel width.

These results show that 3D printing was the least accurate and precise in creating narrow channels due to its limited resolution (600 dpi) in the x- and y-directions. Laser ablation also had low accuracy and precision when making narrow channels because of the melting that occurs on sidewalls during the process; active cooling may likely mitigate this limitation, though.

Table 3: Measured accuracy and precision when creating channels with nominal width 200 μm and 400 μm.

Fabrication Method	Accuracy (Avg. % Error)		Precision (Stdev. % Error)	
	200 μm	400 μm	200 μm	400 μm
Micromilling	2.3%	2.1%	2.7%	2.4%
Laser Ablation	60%	32%	17%	10%
3D Printing	200%	120%	57%	37%

The measured accuracy and precision of the channel depth were defined in the same way as for the channel width. This studied focused on the four channels in the test part with nominal depth 100 μm and varying width. Table 4 shows the measured accuracy and precision of the channel depth. These results show that all three prototyping alternatives have limited accuracy in terms of depth of cut. Laser ablation had the lowest accuracy because of its largely isotropic ablation mechanism. 3D printing suffered because of its limited set of vertical pixels. Finally, micromilling was limited by the tool height offset that had to be visually determined.

Table 4: Measured accuracy and precision when creating channels with nominal depth 100 μm.

Fabrication Method	Accuracy (Avg. % Error)	Precision (Stdev. % Error)
Micromilling	14.6%	0.5%
Laser Ablation	60.6%	9.9%
3D Printing	31.5%	4.4%

Peg roundness was characterized by measuring the maximum and minimum diameters of each set of pegs on the test part. The percent variation shown in Table 5 was the ratio of the difference between the maximum and minimum diameters to the nominal diameter. These results show that laser ablation had the greatest roundness variation likely due to the angle in laser sidewalls relative to other fabrication methods. Micromilling produced the roundest circles because its toolpath is accurate to 0.1 μm.

Table 5: Variation between maximum and minimum measured diameters relative to nominal diameter.

Nominal Diameter (μm)	1000	750	500	250	125
Micromilling	2%	3%	2%	5%	25%
Laser Ablation	23%	50%	57%	52%	50%
3D Printing	9%	9%	12%	9%	16%

Table 6 shows the surface roughness measured at the bottom of the set of channels with depth 100 μm. The surface of the cast acrylic stock was significantly smoother than those created by micromilling and laser ablation. Nonetheless, micromilling resulted in the smoothest finished surface by far.

Table 6: Surface roughness measured at the bottom of the channels with depth 100 μm.

Fabrication Method	∥ to Feed (μm)		⊥ to Feed (μm)	
	R_a	R_q	R_a	R_q
Micromilling	0.34	0.39	0.35	0.39
Laser Ablation	5.73	6.56	6.25	7.13
3D Printing	1.81	2.19	1.68	1.94

The differences observed in Tables 3-6 can be qualitatively observed in the recorded SEM images of each test piece. Images were recorded at two locations: the intersection of two channels and a single peg (see Figure 2). From these images, 3D printing performs the most poorly; the deformation of liquid polymer before UV curing may have caused the lack of definition in any feature. Laser ablation performed slightly better, but the rough sidewalls created by ablation melting and relatively large scallops are not desirable features in a microfluidic device because they can disrupt flow. Micromilling performed the best of the three alternatives, but there are several burrs, which may be reduced with further process refinement.

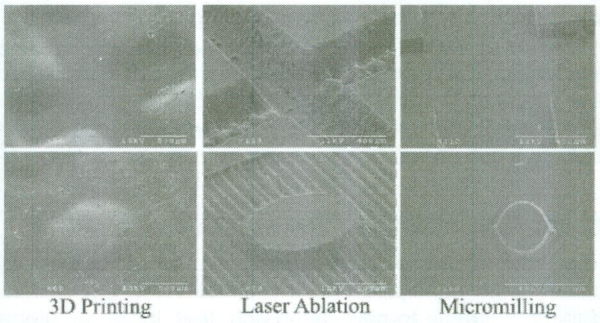

Figure 2: SEM images of a channel intersection and a peg created by each of the three prototyping alternatives.

2.3 Summary

Three alternative prototyping methods were compared for microfluidic applications by using each method to create a designed test piece. The results generally showed an inverse relationship between process time and quality. For example, micromilling required the longest process time but created the most accurate, precise, and smoothest features, while 3D printing was the quickest but produced the least accurate and precise features. Laser ablation created rough, imprecise features that would be sufficient for less demanding applications. All three methods required less time than photolithography, and micromilling in particular was better able to make more 3D geometries. But, none of the three methods produced the expected part quality. Ultimately, though, the alternatives studied in this research have not yet been fully optimized. These results show that further development may in fact make each processing method a highly efficient and effective alternative to photolithography.

3 PRODUCT-CENTERED ENVIRONMENTAL VALUE STREAM MAPPING FOR SMES

Manufacturers increasingly have been required to respond to growing customer demands for green products, increasing government regulation, and increasing and more volatile resource costs [7]. Thus, green manufacturing has become another critical component of advanced manufacturing efforts. While many manufacturers have started developing means to address this trend, small- and medium-sized enterprises (SMEs) have typically lagged behind other manufacturers [8,9]. Some of the reasons for this include the financial, technical, and manpower obstacles unique to SMEs and the focus of SMEs on shorter term financial survival [10]. More importantly, though, SMEs generally treat manufacturing processes as black boxes with assumed consumptions in many of their decisions because they lack applicable tools and posses imperfect data that does not capture the state of every process and tool in their facility [11,12].

Among the different environmental sustainability tools proposed in the literature, value stream mapping (VSM) is perhaps one good choice for SMEs, especially since it is an already familiar tool: studies have shown that 65% of SMEs surveyed already utilize VSM [13]. Furthermore, because VSMs are already a lean manufacturing tool used to optimize the flow of material, information, and people, it can be extended easily to consider both financial and ecological factors [14]. VSMs also represent a product-centered approach that enables analysis over an entire process chain, which limits the risk of offsetting impacts, ensures the viability of the entire process chain, and allows for easy identification of critical environmental hotspots. This project presents such an environmental VSM (EVSM) approach for SMEs, describes how it can be used, and validates it for a simple process chain.

3.1 Environmental Value Stream Mapping Approach

There have been several efforts to incorporate green manufacturing principles into traditional VSM approaches, including a cradle-to-gate approach that looks at global warming emissions (GWP) across the facility and supply chain [15], toolkits that use additional performance indicators (e.g., consumption of water, energy, electricity, gas, pressurized air, or material wastes) [16-18], and more detailed frameworks that look across many levels of the manufacturing facility (e.g., machine tool to process) [19]. This proposed framework builds upon these previous approaches by using a gate-to-gate structure based on the OECD Sustainable Manufacturing Toolkit that focuses on all process chains within the facility. Ultimately, the goal of this structure is to determine the key environmental hotspots in the process chain so that improvements can be easily suggested and quantified for decision-makers.

The first step is to select the correct process chain within the facility for further examination so that improvement resources are efficiently allocated. Product-related criteria (e.g., cumulative power rating or average margin/product) can be used to determine the likely "hotspot" process chain responsible for the greatest share of environmental impact. Here, a product-process matrix provides a holistic overview of each process chain to simplify the analysis.

Once a process chain has been selected, each process within the chain must be measured to calculate the key performance indicators (KPIs). This approach focuses on three forms of consumption: energy used, material removed, and coolant supplied. These values then allow for a GWP emission estimation, which serves as a KPI of environmental impact. Because many environmental impacts in manufacturing are also tied to the process cycle time, the cycle time is also measured as a KPI. In addition, the input raw material for the process chain and its embodied GWP emissions are also included in the final KPI calculations to complete the gate-to-gate analysis.

When the current state of the process chain is characterized, a manufacturer can identify the processes with highest environmental impact and target those specific processes for improvement. The EVSM approach can then be repeated in order to determine the extent to which the selected solutions reduce environmental impact while preserving the feasibility of the process chain.

3.2 Experimental Validation

The proposed methodology was used to study a process chain that created the blind flange shown in Figure 3. This part was made from AISI 304 stainless steel and designed to replicate flanges primarily used in the chemical and food industries to close off pipes.

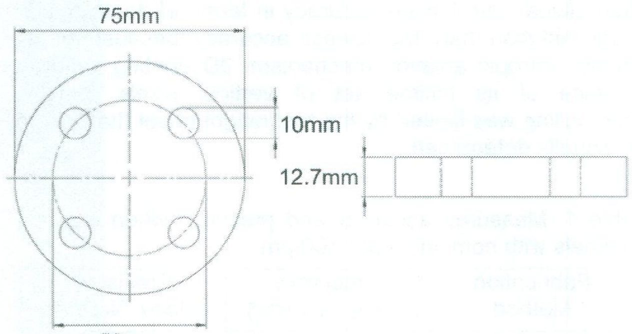

Figure 3: Dimensioned drawing of blind flange created by test process chain.

The process chain for the blind flange utilized five steps:

- External turning was performed on a Mori Seiki Dura Turn 1530 two axis CNC lathe using carbide inserts (Kennametal CNMG432 KC850). The cutting speed was 45 m/min; the feed and depth of cut was 0.254 mm/rev and 0.345 mm, respectively for roughing and 0.1016 mm/rev and 0.255 mm, respectively for finishing. The length of each cut was 30 mm and coolant was supplied.
- Sawing was performed on a Marvel 8-Series I vertical band saw. The cutting speed was 30 m/min and the blade thickness was 1.143 mm. Gravity was used to feed the blade through the material and coolant was supplied.
- Face turning was also performed on a Mori Seiki Dura Turn 1530 using the same carbide inserts. The cutting speed was 30 m/min, the feed was 0.1016 mm/rev, and the depth of cut was 0.635 mm. Both sides of the blind flange were faced and coolant was supplied.
- Drilling was performed on a Haas VF-0 three axis machining center using an HSS-Co drill with 10 mm diameter and 135° point angle. The cutting

speed was 12 m/min and the feed was 0.1 mm/rev. Coolant was supplied.

- Deburning was performed on a Bridgeport Series-1 manual mill using a 90° HSS deburring tool (MA Ford 61100003). The cutting speed was 3 m/min, parts were hand-fed, and no coolant was used.

The demanded power and supplied coolant were measured for each step in the process chain except deburring (since no coolant is needed for deburring). Power measurements were made using a Yokogawa CW240 meter with 50 A CTs sampling at 10 Hz and configured for a three wire-three phase-three load measurement. From these power measurements, the process (value-added), auxiliary (non-value-added), and cycle (total) time and energy were calculated. The volumetric flow rate of the supplied coolant was estimated by filling a beaker over 10 seconds. Finally, the material removed was calculated based on the process parameters. Table 7 summarizes these measurements.

Table 7: Summary of EVSM results for blind flange process chain.

Process Step	Cycle Time (s)	Cycle Energy (Wh)	Material Removed (g)
Ext. Turning	120	36.2	16.9
Sawing	343	36.1	39.9
Face Turning	232	75.0	44.3
Drilling	248	63.1	31.5
Deburring	80	7.8	0.0
TOTAL	1023	218.2	132.6

Based on the measurements in Table 7, GWP emissions were calculated assuming an emissions conversion factor of 545 g CO_2-eq/kWh for electricity in the United States [20] and 3.46 g CO_2-eq/g and 1.6 g CO_2-eq/g of the input and recycled stainless steel, respectively [21]. The total GWP emissions for the blind flange process chain were 1792.4 g CO_2-eq/part. These emissions were primarily driven by the embedded GWP emissions in the raw material used to create the part.

The VSM created using these results highlighted the face turning and drilling operations as the "hotspot" processes most responsible for the environmental impact of the entire process chain. Further investigation of the drilling process found that increasing the process rate by using a cemented carbide drill coated with TiAlN reduced the cycle time by 123 seconds and cycle energy by 39.4 kWh, which represents an 18% energy reduction.

3.3 Summary of EVSM Approach

An EVSM approach was proposed and validated in this project. Using this tool for a blind flange process chain highlighted opportunities to improve the face turning and drilling steps. Focusing on the drilling step, process parameter optimization and the use of coated carbide drills resulted in a potential energy savings of 18%.

There are several ways that this method may be improved. First, material emissions should also consider the GWP emissions from other consumables and supplies, such as metalworking fluids and cutting tools. Financial indicators may also be more directly incorporated to better understand payback periods for different decisions. More importantly, though, manufacturing impacts other life cycle stages, particularly the use phase [22]. Thus, any improvement decision should consider these effects to ensure that the finished product will not offset impacts.

4 ANALYZING THE IMPACT OF MANUFACTURING DECISIONS ON THE PRODUCT LIFE CYCLE

Manufacturers have started to embrace sustainability especially as they have grown increasingly responsible for larger portions of the product life cycle. But, they have been unable to fully synthesize sustainability into decision-making because they do not fully understand the role of manufacturing in the product life cycle. For example, higher quality products tend to have higher efficiency and longer service life [22]. Thus, manufacturers have been unable to leverage processes to optimize the entire life cycle.

Leveraging refers to exploiting the inherent relationship between part features or characteristics and the subsequent functionality of the finished product [23]. This relationship implies that manufacturing has two sets of impacts on the product life cycle: direct (those affecting the resources required creating parts) and indirect (those affecting the use or end-of-life performance via generated part features or characteristics). Previous research has shown that for many products, especially those with relatively large use phase impacts, the increased environmental impact of small improvements in the manufacture of the product are dwarfed by the even greater savings in the use of the improved product [22].

The goal of this project is the development of simple visual tools that facilitate manufacturing decision-making by showing how different combinations of process parameters impact environmental and technical constraints across the entire product life cycle. Thus, not only are environmental impacts considered holistically, but the technical feasibility (e.g., minimal maintenance costs or system variability) of any green manufacturing strategy can be ensured.

The approach advocated by this research is analogous to the Ashby approach for material selection. An optimization equation would be defined in terms of the process constraints and parameters. By superimposing constraints on a plot of combinations of process parameters with their subsequent environmental impact, manufacturers can easily identify ideal processing ranges to exploit (see Figure 4). This approach, though, has substantial data requirements. Specifically, empirical manufacturing relationships that describe environmental impact, resource usage, technical performance (e.g., tool wear), and product quality must be developed, as well as relationships between a part's features and its performance (e.g., efficiency). We are currently studying gear and turbine vane manufacturing to generate much of this data.

5 SUMMARY

This paper has described three projects that utilize machining to develop advanced manufacturing technology. The first project focused on shortening the time from design to product by comparing rapid prototyping alternatives for microfluidic devices. The second project developed an environmental value stream mapping approach so that SMEs could more easily and effectively identify and improve areas with high environmental impacts. Finally, the last project is creating tools that enable manufacturers to fully understand and exploit the role of manufacturing in the product life cycle. Ultimately, the goal of each project is to help manufacturers more easily face and respond to future limitations whether those are driven by customers who want new products faster or by regulations and demands for reduced environmental impact.

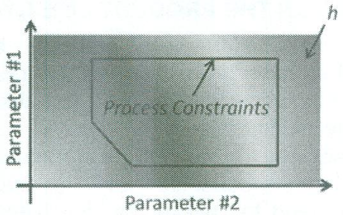

Figure 4: Example of proposed visual process parameter selection tool for manufacturing; green indicates optimal environmental impact.

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University of California, Berkeley

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SUSTAINABLE MANUFACTURING PARTNERSHIP

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Technology that improves manufacturing processes by...

Shortening time from design to finished product	(1) Rapid Prototyping for microfluidic applications
Addressing future limitations and challenges (e.g., sustainability)	(2) Environmental value stream mapping for SMEs (3) Impact of mfg decisions on product life cycle

Slide 1

Berkeley

Rapid Prototyping for Microfluidics

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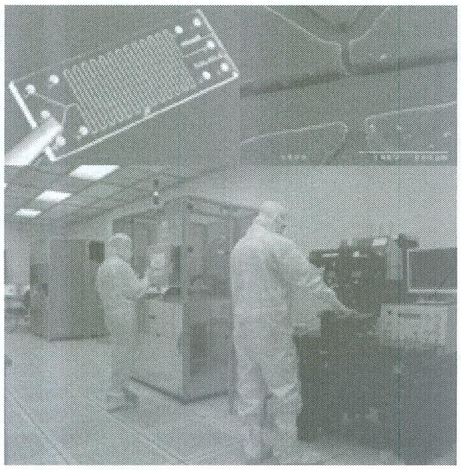
- Typically produced using photolithography techniques
- Limitations:
  - Lacks ability to create complex 3D geometries
  - Limited to few materials
  - Requires many chemicals and consumables
  - Requires multiple steps and long processing times
  - Is expensive



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Alternative Rapid Prototyping Approaches

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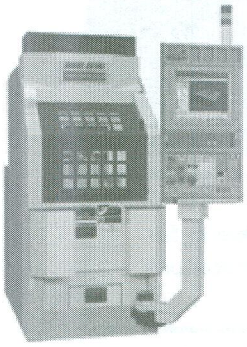

Micromilling
Mori Seiki NVD1500 Machining Center

Laser Ablation
ULS PLS6MW

3D Printing
Objet Connex350

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Test Part

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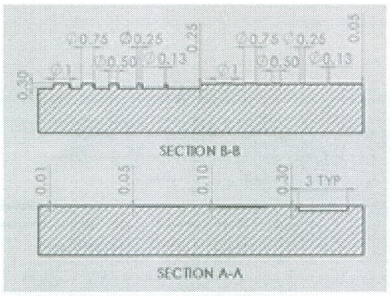

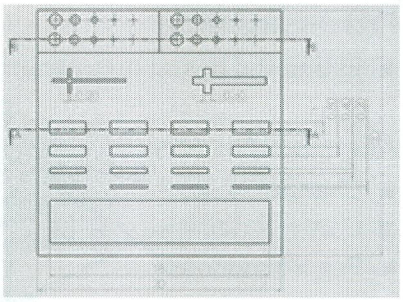

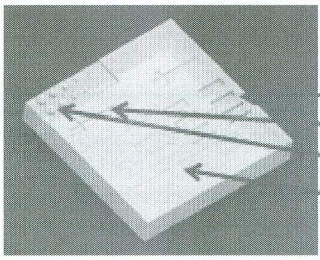

- Includes several key features:
  - Channel arrays
  - Intersecting channels
  - Round pegs
  - Flat planes

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Processing Methodology

LMAS

- Micromilling
  - Fixtured with parallels and spring
  - Uncoated carbine 2-flute endmills
  - Speed/feed based on mfg. spec.
  - Full depth of cut for each feature
  - Width of cut
    - 100% tool diameter (sloting)
    - 50% tool diameter (facing)
- Laser ablation
  - Empirically defined DOC, speed, power, and pulse modulation relationship
- 3D printing
  - "Glossy" finish
  - Part thickness oriented in z-direction

Tool Diameter (mm)	Spindle Speed (RPM)	Feed Rate (mm/min)
1	30000	80
0.4	40000	45
0.2	40000	22

20x20x6.35 mm cast acrylic stock material

VeroClear RGD810 (transparent thermoplastic)

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Metrology

LMAS

- Processing time
  - Estimated based on toolpath
- Accuracy/precision
  - Channel width
  - Channel depth
  - Peg Roundness
- Part quality
  - Surface roughness
  - Qualitative analysis

Keyence VHX-500F optical microscope:
- 2.11 MP CCD with 1628x1236 pixels
- Resolution @ 10x = 600 nm

Alpha Step IQ surface profilometer:
- Stylus tip = 6 µm tip diameter; 60° taper
- Step height = 750 µm
- Max scan height = 2 mm
- Resolution = 12 nm

Hitachi S-2460N variable vacuum SEM:
- 41 magnification steps (20-200000x)
- Resolution = 4 nm @ high vacuum
- Coated test parts with 150 Å gold layer

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Processing Time

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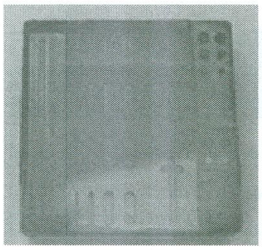

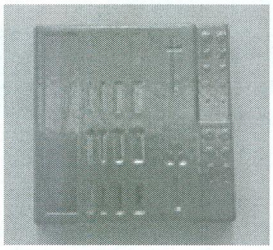

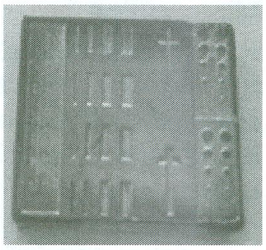

Micromilling	Laser Ablation	3D Printing
• 8 h to 1st prototype • 2 h for subsequent prototypes	• 4 h to 1st prototype • 10 min for subsequent prototypes	• 30 min to 1st prototype • 30 min for subsequent prototypes

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Accuracy/Precision: Channel Width & Depth

LMAS

- Accuracy/precision defined as average and standard deviation of percent error for four channels
  - Channel width: 2 sets (200 µm and 400 µm nominal width)
  - Channel depth: 1 set (100 µm nominal depth)

Channel Width	Accuracy (Avg. % Error)		Precision (Stdev. % Error)	
	200 µm	400 µm	200 µm	400 µm
Micromilling	2.3%	2.1%	2.7%	2.4%
Laser Ablation	60%	32%	17%	10%
3D Printing	200%	120%	57%	37%

Channel Depth	Accuracy (Avg. % Error)	Precision (Stdev. % Error)
Micromilling	14.6%	0.5%
Laser Ablation	60.6%	9.9%
3D Printing	31.5%	4.4%

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Accuracy/Precision: Peg Roundness

LMAS

- Percent variation is ratio of the difference between maximum and minimum diameters to the nominal diameter

Nominal Diameter (µm)	1000	750	500	250	125
Micromilling	2%	3%	2%	5%	25%
Laser Ablation	23%	50%	57%	52%	50%
3D Printing	9%	9%	12%	9%	16%

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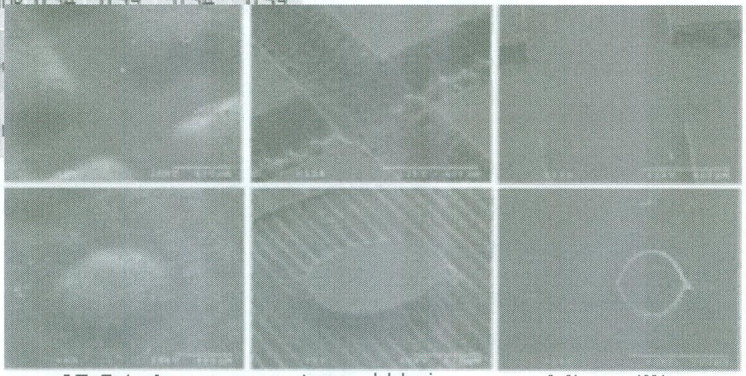
Part Quality

LMAS

Fabrication Method	Parallel To Feed		Perpendicular To Feed	
	R_a	R_q	R_a	R_q
Micromilling	0.34	0.39	0.34	0.39
Laser Ablati[illegible]				
3D Printi[illegible]				



3D Printing Laser Ablation Micromilling

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Summary of Rapid Prototyping Comparison

LMAS

Process	Time to Prototype	Feature Quality	Takeaway
3D Printing	30 min	Unacceptable	Simple
Laser Ablation	4 hours	Acceptable	Fast
Micro-milling	8 hours	Good	Potential Alternative
Photo-lithography	Days	Excellent	Industry Standard

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Environmental Value Stream Mapping (EVSM)

LMAS

- Need to incorporate sustainability into decision-making
  - Growing customer demand
  - Increasing government regulations
  - Increasing and more volatile resource costs
- SMEs have lagged other manufacturers, though
  - Financial, technical, and manpower obstacles
  - Focus on shorter term financial survival
- Mfg processes = black box
  - SMEs lack appropriate tools
  - SMEs lack good data

Product-Centered Environmental Value Stream Mapping (EVSM)

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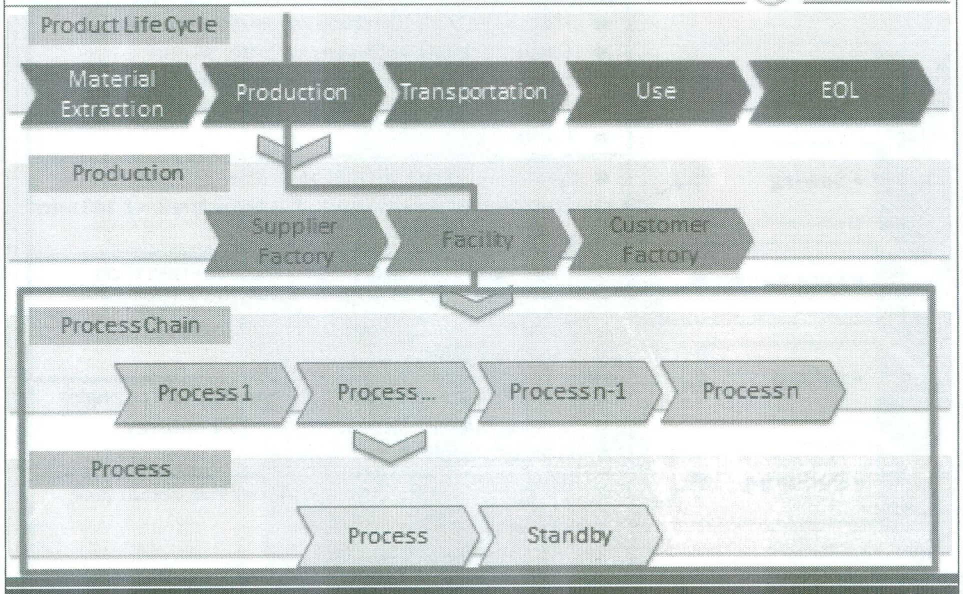
EVSM Boundaries

LMAS



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Experimental Validation: Blind Flange

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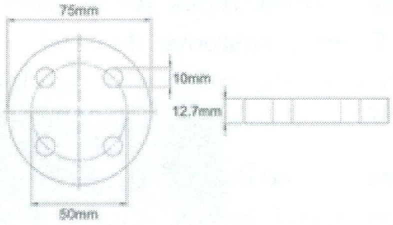
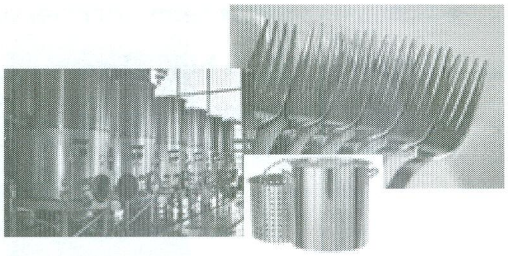
- Primarily used in chemical and food industry
- Closes off pipes
- Made from AISI 304 stainless steel





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Blind Flange Process Chain

LMAS

1. External Turning
   - Mori Seiki Dura Turn 1530 w/ carbide insert tools
   - Cutting speed = 45 m/min; Length = 30 mm
   - Feed/DOC (Roughing) = 0.254 mm/rev + 0.345 mm
   - Feed/DOC (Finishing) = 0.1016 mm/rev + 0.255 mm
   - Coolant supplied
2. Sawing
   - Marvel 8-Series I vertical band saw
   - Cutting speed = 30 m/min; Blade thickness = 1.143 mm
   - Coolant supplied
3. Face Turning
   - Mori Seiki Dura Turn 1530 w/ carbide insert tools
   - Cutting speed = 30 m/min; Both faces machined
   - Feed/DOC = 0.1016 mm/rev + 0.635 mm
   - Coolant supplied
4. Drilling
   - Haas VF-0 w/ HSS-Co drill (10 mm dia; 135° pt angle)
   - Cutting speed/Feed = 12 m/min + 0.1 mm/rev
   - Coolant supplied
5. Deburring
   - Bridgeport Series-1 manual mill w/ HSS deburr tool
   - Cutting speed = 3 m/min
   - No coolant supplied

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EVSM of Blind Flange

LMAS

1. External Turning
2. Sawing
3. Face Turning
4. Drilling
5. Deburring

Process Step	Cycle Time (s)	Cycle Energy (Wh)	Material Removed (g)
External Turning	120	36.2	16.9
Sawing	343	36.1	39.9
Face Turning	232	75.0	44.3
Drilling	248	63.1	31.5
Deburring	80	7.8	0.0
TOTAL	***1023***	***218.2***	***132.6***

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Summary of EVSM Approach

LMAS

- Total GWP emissions = 1792.4 g CO_2-eq/part
  - Primarily driven by embedded GWP emissions
- "Hotspot" processes are face turning and drilling
  - Using TiAlN coated cemented carbide tool and optimizing process rate yielded:
    - Cycle time reduction of 123 seconds
    - Cycle energy reduction of 39.4 kWh (= 18% savings)
- Future improvements:
  - Complete material emissions (e.g., metalworking fluids, tools)
  - Financial indicators
  - Impact of manufacturing on other life cycle stages (e.g., product quality)

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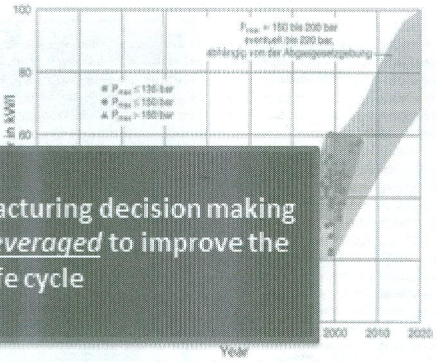
Mfg in the Product Life Cycle

LMAS

- Manufacturers increasingly responsible for larger portions of product life cycle
- Sustai[...] been [...] decisi[...]
- Manufacturers unable to fully exploit processes to optimize life cycle

Develop tools to aid manufacturing decision making so that processes may be *leveraged* to improve the product life cycle



Change in power density of Daimler diesel engines [Berger 2003]

Increase in performance due to improved tolerance and precision in manufacture of powertrain components

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Leveraging Manufacturing Precision

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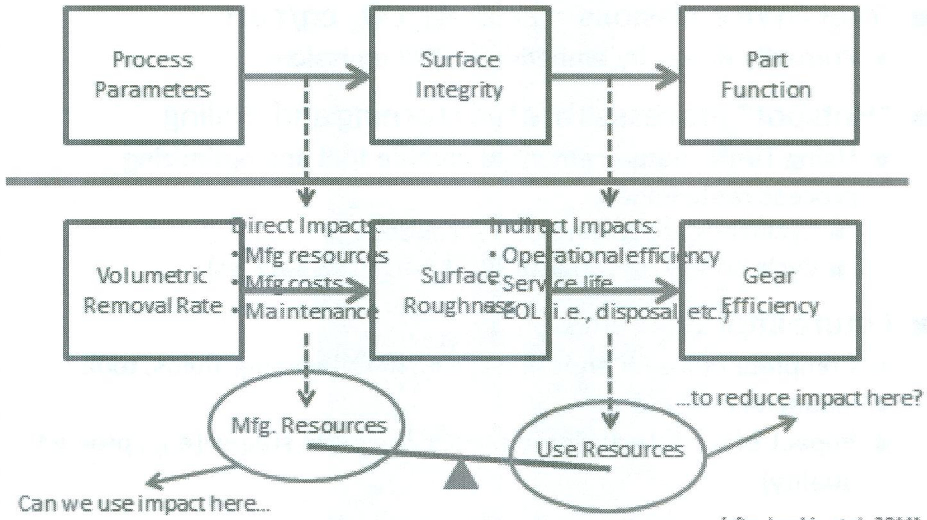

[after Jawahir, et al. 2011]

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Manufacturing Decision-Making Tools

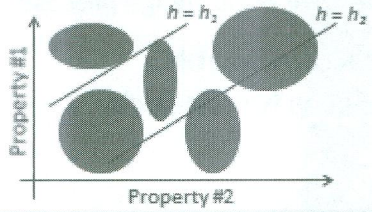
LMAS

Ashby approach

- Define optimization equation as follows:

$$M = f(\text{FunctionalRequirements}) * g(\text{SpecifiedGeometry}) * h(\text{MaterialProperties})$$

- Plot properties in *h* to guide optimization:

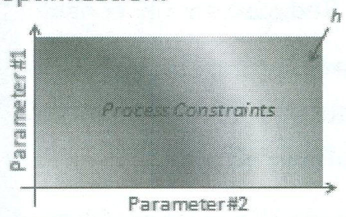


Manufacturing approach

- Define optimization equation as follows:

$$M = f(\text{Constraints}) * h(\text{ProcessParameters})$$

- Plot parameters in *h* to guide optimization:



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Requirements for Tool Development

LMAS

- Empirical manufacturing relationships:
  - Data should come from similar (if not exact) process/equipment
  - Should at least include:
    - Resource usage & environmental impact (e.g., energy, water)
    - Mfg system performance (e.g., tool wear, availability, throughput)
    - Mfg output (e.g., achieved surface integrity) ***
  - Similar to burr control charts or CO2PE?
- Product-specific use relationships
- Other considerations:
  - Efficiency -> Optimization equation
  - Effectiveness -> Process constraints
  - Part functionality

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Summary

LMAS

- Compared alternative rapid prototyping methods for microfluidics
  - Micromilling created features with better accuracy, precision, and quality, but it still needs further development
- Validated environmental VSM approach for SMEs to identify and improve processes with high environmental impact
  - Reduced energy consumption by 18% for blind flange process
- Developing decision-making tools that enable manufacturers to leverage processes for life cycle optimization

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- UCB ME Student Machine Shop
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- Nuo Zhang

MTTRF

MORI SEIKI THE MACHINE TOOL COMPANY

DTL Corporation

ESPRIT The Right Choice

SUSTAINABLE MANUFACTURING PARTNERSHIP

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