Outline

- Introduction to Manufacturing
  - Parts Fabrication and Assembly
  - Metrics: Quality, Rate, Cost, Flexibility
  - Water Jet Cutting
- Video Sequence B777 Manufacturing
  - Role of Manufacturing in a Real World Context
- OMax Introduction
  - Computer Aided (Assisted) Manufacturing
  - Converting a drawing to CNC Routing Instructions
Course Flow Diagram

Learning/Review

- Design Intro
- CAD/CAM/CAE Intro
- FEM/Solid Mechanics Overview
- Manufacturing Training
- Structural Test “Training”
- Design Optimization

Problem statement

Hand sketching

CAD design

FEM analysis

Produce Part 1

Test

Optimization

Produce Part 2

Test

Final Review

Deliverables

Design Sketch v1

Drawing v1

Analysis output v1

Part v1

Experiment data v1

Design/Analysis output v2

Part v2

Experiment data v2

Due Wed, Jan 21
Introduction to Manufacturing

- Manufacturing is the *physical realization* of the previously designed parts
- Metrics to assess the “performance” of mfg
  - Quality
    - does it meet specifications?
  - Rate
    - how many units can we produce per unit time?
  - Cost
    - What is the cost per unit?
    - What is the investment cost in machinery & tooling?
  - Flexibility
    - what else can be make with our equipment?
    - How long does it take to reconfigure the plant?
Life Cycle: Conceive, Design, Implement

- **Beginning of Lifecycle**
  - SRR
    - Mission
    - Requirements
    - Constraints

- **Conceive**
  - creativity
  - architecting
  - trade studies

- **Design**
  - “process information”
  - modeling simulation
  - experiments
  - design techniques
  - optimization (MDO)

- **Implement**
  - “turn information to matter”

- **The System**
  - Architect
  - Designer
  - System Engineer

- **The Enterprise**
  - Manufacturing assembly integration

- **The Environment**: technological, economic, political, social, nature
Raw Materials

- Material Selection
  - Strength
  - Density
  - Cost
  - ...

- Form
  - Sheet
  - Rods, ...

16.810 (16.682)
Parts Manufacturing

- example: deck components
  - Ribbed-bulkheads
  - Approximate dimensions
    - 250mm x 350mm x 30mm
    - Wall thickness = 2.54mm

- Fundamental Parts Fabrication Techniques
  - Machining – e.g. milling, laser and waterjet cutting ...
  - Forming – e.g. deep drawing, forging, stamping
  - Casting - fill die with liquid material, let cool
  - Injection Molding - mainly polymers
  - Layup – e.g. Pre-preg composite manufacturing
  - Sintering - form parts starting from metal powder
Metal Cutting/Removal Techniques

Turning on a lathe
Milling
Planing
Slotting
Grinding
Reaming

New Techniques:
- Laser Cutting (mainly for sheet metal)
- Waterjet Cutting
Quality: Engineering Tolerances

- Tolerance -- The total amount by which a specified dimension is permitted to vary (ANSI Y14.5M)
- Every component \( p(y) \) within spec adds to the yield (\( Y \))
Process Capability Indices

- **Process Capability Index**
  \[ C_p \equiv \frac{(U - L)}{3\sigma} \]

- **Bias factor**
  \[ k \equiv \frac{\mu - \frac{U + L}{2}}{(U - L)/2} \]

- **Performance Index**
  \[ C_{pk} \equiv C_p (1 - k) \]
Rate: Manufacturing

- Typically: # of units/hour
- The more parts we make (of the same kind), the lower the cost/unit
  - Learning Curve effects
    - Higher Speed - Human learning
    - Reduced setup time
    - Fewer Mistakes (= less scrap = higher yield)
- Bulk quantity discounts (=economies of scale)
  - Better negotiating position with suppliers of raw materials and parts
Learning Curve Equation

- Credited to T.P. Wright [1936]
- Model cost reduction between first production unit and subsequent units
  - Model the total production cost of $N$ units

$TFU = \text{Theoretical first unit cost}$

$S = \text{learning curve slope in } \%$

--> percentage reduction in cumulative average cost, each time the number of production units is doubled

**Recommended:**

$2 < N < 10 \quad S = 95\%$

$10 < N < 50 \quad S = 90\%$

$N > 50 \quad S = 85\%$

$$C_{total} (N) = TFU \cdot N^B$$

$$B \equiv 1 - \frac{\ln(100\%/S)}{\ln 2}$$

**S=90% Learning Curve**

- $S=90\%$
- $B=0.85$
- $TFU=1$
Cost: Driving Factors

- Cost/Unit [$]
  - Depends on
    - Manufacturing process chosen
    - Number of Parts made
    - Skill and Experience of worker(s), Salary
    - Quality of Raw Materials
    - Reliability of Equipment
    - Energy Costs
    - Land/Facility Cost
    - Tolerance Level (Quality)
**Process Selection**

Total Manufacturing Cost [$]

Choose 2 Choose 1

Total Cost process 2

Total Cost process 1

Fixed cost process 1

Fixed cost process 2

E.g. Stamping

E.g. Waterjet Cutting

\[ C_{tot} (N) = C_{fixed} + C_{var} \cdot N \]

- Machine
- Tools
- Training
- Time/part
- Material
- Energy

N - number of parts produced
Flexibility: Uncertainties

- Short market cycles
- Distinct customers with changing needs
- Changes in laws, regulations & standards
  - Uncertainties in products and, therefore, in single parts!
- How to address these uncertainties?
  - Flexibility as ‘Magic bullet’?
Flexibility of process technologies

- Flexibility is the ease with which a system can change from one state to another!
- Which process is more flexible than others?

What type of flexibility?

\[
\begin{bmatrix}
C_{\text{var}} \\
C_{\text{fix}}
\end{bmatrix}
\]

- High Speed Machining
- Forming technology
- Punching
- Casting
- Prototyping

Set-up time

Output rate
Types of Flexibilities and their Linkage

Component or Basic Flexibilities

- Organizational Structure
- Machine
- Material Handling
- Operation

System Flexibilities

- Process
- Routing
- Product
- Volume
- Expansion

Aggregate Flexibilities

- Program
- Production
- Market

Microprocessor Technology
Waterjet - Brief history

- Industrial uses of ultra-high pressure waterjets began in the early 1970s. Pressures: 40,000 ~ 60,000 psi
  Nozzle diameter: 0.005"

- Special production line machines were developed to solve manufacturing problems related to materials that had been previously been cut with knives or mechanical cutters.

- Examples of early applications
  Cardboard
  Shapes from foam rubber
  Soft gasket material
- In the early 1990s, John Olsen (pioneer of the waterjet cutting industry) explored the concept of abrasive jet cutting.

- The new system equipped with a computerized control system that eliminated the need for operator expertise and trial-and-error programming.

- Olsen teamed up with Alex Slocum (MIT) Used cutting test results and a theoretical cutting model by Rhode Island University. Developed a unique abrasive waterjet cutter.
Pumps

Intensifier Pump

- Early ultra-high pressure cutting systems used hydraulic intensifier pumps.
- At that time, the intensifier pump was the only pump for high pressure
- Engine or electric motor drives the pump

Pressure: ~ 60,000 psi
Crankshaft pumps
- Use mechanical crankshaft to move any number of individual pistons
- Check valves in each cylinder allow water to enter the cylinder as the plunger retracts and then exit the cylinder into the outlet manifold as the plunger advances into the cylinder.

Pressure: ~ 55,000 psi
Reliability is higher.

Actual operating range of most systems: 40,000 ~50,000 psi

An increasing number of abrasivejet systems are being sold with the more efficient and easily maintained crankshaft-type pumps.
Two-stage nozzle design

[1] Water passes through a small-diameter jewel orifice to form a narrow jet. Then passes through a small chamber pulling abrasive material

[2] The abrasive particles and water pass into a long, hollow cylindrical ceramic mixing tube. The resulting mix of abrasive and water exits the mixing tube as a coherent stream and cuts the material.

Alignment of the jewel orifice and the mixing tube is critical

In the past, the operator adjusted the alignment often during operation.
X-Y Tables

Separate

Integrated

Gantry

Cantilever

Cutting table
X-Y Tables

**Gantry**

Well-adapted to the use of multiple nozzles for large production runs

Loading material onto the table can be difficult because the gantry beam may interfere, unless the gantry can be moved completely out of the way

Because the gantry beam is moved at both ends, a very high-quality electronic or mechanical system must be employed to

**Cantilever**

Y-axis is limited in length to about 5 feet because of structural considerations
X-Y Tables

Separate

More expensive to build than the traditional separate frame system

Inherently better dynamic accuracy because relative unwanted motion or vibration between the table and X-Y structure is eliminated

System accuracy can be built at the factory and does not require extensive on-site set-up and alignment

Less floor space is required for a given table size because the external support frame is eliminated

Integrated
Waterjet in Aero/Astro machine shop

OMAX Machining Center 2652

Integrated cantilever

<table>
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<tr>
<th>Work Envelope</th>
<th>X-Y Travel &quot;</th>
<th>52&quot; x 26&quot;</th>
<th>(1.3 m x 0.7 m)</th>
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<table>
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<th>Accuracy of Motion at 70 degrees F</th>
<th>Over entire travel</th>
<th>±0.003&quot;</th>
<th>(0.076 mm)</th>
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<td>Over 1 foot travel</td>
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<td>Repeatability</td>
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<td>Squareness</td>
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<td>Straightness</td>
<td>0.0017&quot; per ft</td>
<td>(0.14 mm/in)</td>
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<tr>
<td>Backlash</td>
<td>0.0007&quot; max</td>
<td>(0.018 mm)</td>
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The OMAX control system computes exactly how the feed rate should vary for a given geometry in a given material to make a precise part.

The algorithm actually determines desired variations in the feed rate every 0.0005" (0.012 mm) along the tool path.

OMAX uses a PC to compute and store the entire tool path and feed rate profile and then directly drive the servo motors that control the X-Y motion.
How to Estimate Manufacturing Cost?

(1) Run the Omax Software!
- Estimated time to make this part: 3.265 min.
- Estimated cost to make this part: $4.08

(2) Estimation by hand

\[ \text{Cost}_{\text{manufac}} = C_0 t_{\text{manufac}} \]

\[ t_{\text{manufac}} = t_{\text{cutting}} + t_{\text{traverse}}, \quad t_{\text{cutting}} \gg t_{\text{traverse}} \]

\[ \simeq t_{\text{cutting}} \]

\[ = \sum_i \frac{l_i}{u_i} \]

- Break up curves into linear and nonlinear sections
- Measure curve lengths and calculate cutting speeds
- Solve for cutting times for each curve and sum

Overhead cost estimate in Aero/Astro machine shop
How to Estimate Manufacturing Cost?

- **Linear cutting speed,** \( u_{linear} \)
  - Good approximation for most of the curves in the CAM waterjet cutting route

- **Arc section cutting speed,** \( u_{arc} \)
  - Assume if arc radius is less than \( R_{min} \)

- **Reduce manufacturing time**
  - Reduce the total cutting length
  - Increase fillet radii
  - Reduce cutting curve lengths

\[
\begin{align*}
 u_{linear} &= \left( \frac{42.471}{q} \right)^{1.15} \quad \text{[in/min]} \\
 u_{arc} &= \left[ 1.866R + 9.334e^{-4} \right]^{1.15} \quad \text{[in/min]}
\end{align*}
\]

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<th>Quality Index, ( q )</th>
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<td>( R_{min} ) (in)</td>
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Best applications

Materials and thickness

- Aluminum, tool steel, stainless steel, mild steel and titanium
- Thicknesses up to about 1" (2.5 cm)

Shapes

- An abrasivejet can make almost any two-dimensional shape imaginable—quickly and accurately—in material less than 1" (25 mm) thick.
- The only limitation comes from the fact that the minimum inside radius in a corner is equal to $\frac{1}{2}$ the diameter of the jet, or about 0.015" (0.4 mm).
Applications that are generally poor

Low-cost applications where accuracy really has no value

Using a precision abrasivejet as a cross-cut saw
- Just buy a saw!

Applications involving wood
- It's hard to beat a simple jigsaw.

Parts that truly require a 5-axis machine
- This is a much more specialized market.
Material

Aluminum

Aluminum is a light weight but strong metal used in a wide variety of applications.

Generally speaking, it machines at about twice the speed as mild steel, making it an especially profitable application for the OMAX.

Many precision abrasivejet machines are being purchased by laser shops specifically for machining aluminum. Aluminum is often called the "bread and butter" of the abrasivejet industry because it cuts so easily.

A part machined from 3" (7.6 cm) aluminum; Intelli-MAX software lets you get sharp corners without wash-out
Examples

An example of two aluminum parts done in ½” (1.3 cm) thick aluminum, which took approximately five mintues to machine.

A prototype linkage arm for the Tilt-A-Jet. This part was first "roughed out" on the OMAX. The holes were then reamed out to tolerance, and some additional features (such as pockets) added with other machining processes.

This piece was made from 8” (200mm) thick aluminum as a demonstration of what an abrasive jet can do.
References

### Spiral Development (DSM)

<table>
<thead>
<tr>
<th></th>
<th>1 – Requirements Analysis</th>
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<th>4 – FEM Analysis</th>
<th>5 – Design Optimization</th>
<th>6 – Make Drawing (.dxf)</th>
<th>7 – CAM Layout (.ord)</th>
<th>8 – Manufacture (Omax)</th>
<th>9 – Structural Testing</th>
<th>10 – Accept Part</th>
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