Keynote Lecture

Variable Axis Additive Manufacturing of Metallic Objects

K.P. Karunakaran, IIT Bombay, India
Alain Bernard, IRCCyN, ECN, France
Prathamesh Joshi, IIT Bombay, India

18th European Forum on Additive Manufacturing
June 24-27, 2013
Outline

• Routes of AM
• Hybrid Layered Manufacturing (HLM)
• 5-Axis HLM – Indexed
• 5-Axis HLM – Continuous
• Future Plans
• Conclusions
Routes for AM
Routes for AM

Laminated Manufacturing: LOM, Ultrasonic consolidation, …

Writing on Powder-bed: Zcorp’s 3DP, SLS, Arcam, …

Deposition (Powder-feed*): LENS, LAM, POM, HLM …

Less popular

Most popular
## Routes for AM
### Comparison of Powder-bed and Deposition routes

<table>
<thead>
<tr>
<th>Charact.</th>
<th>Powder-Bed Technologies</th>
<th>Deposition Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>- Only powder</td>
<td>+ Powder (powder-feed), wire and strip</td>
</tr>
<tr>
<td>Material feeding</td>
<td>+ Powder particles are coarse (&gt; 20µm); so, mechanical spreading.</td>
<td>- If powder, particles are fine; so, fluidized feeding using Argon. Complex and costly. + Wire/strip are easy to feed using pinch wheels.</td>
</tr>
<tr>
<td>Support mech.</td>
<td>+ Inherent support mechanism.</td>
<td>- Explicit support mechanism is required. We use 5-axis!</td>
</tr>
<tr>
<td>Gradient matrix</td>
<td>- Not readily amenable for FGM (exception: 3DP)</td>
<td>+ Readily amenable for FGM</td>
</tr>
<tr>
<td>Bonding</td>
<td>Fusion using Laser/ EB/ arc</td>
<td></td>
</tr>
</tbody>
</table>
## Routes for AM

Our choices for Hybrid Layered Manufacturing (HLM)

<table>
<thead>
<tr>
<th>Character</th>
<th>Preference</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech.</td>
<td>Dep. to powder-bed; Hybrid (+&amp;-)</td>
<td>Amenability for gradient matrix</td>
</tr>
<tr>
<td>Bonding</td>
<td>Fusion to binding</td>
<td>Binder has poor green strength.</td>
</tr>
<tr>
<td>Energy source</td>
<td>Arc (MIG &amp; TIG deposition). Soon laser.</td>
<td>budget constraints forced us to choose arc initially. MIG, TIG &amp; laser have their own applications.</td>
</tr>
<tr>
<td>Raw material</td>
<td>Wire (and strip soon) to powder. Multi-wires with diff. feeding in future.</td>
<td>Ease of feeding and 100% yield as against 10-20% in case of powder. Saving in Argon also.</td>
</tr>
<tr>
<td>Motion platform</td>
<td>CNC machine to robot.</td>
<td>Robot is not rigid enough to do machining on the same platform.</td>
</tr>
<tr>
<td>Support mech.</td>
<td>5-axis machine with vertical spindle and table swivels</td>
<td>It is not possible to have a sacrificial support. No support removal too!</td>
</tr>
<tr>
<td>Capabilities</td>
<td>Comp./gradient matrix, conf. channels, disc. adap. Layer.</td>
<td>As deposition is used.</td>
</tr>
</tbody>
</table>
Hybrid Layered Manufacturing (HLM)
Hybrid Layered Manufacturing (HLM)

3-axis HLM

5-axis HLM

Multiple torches
Hybrid Layered Manufacturing (HLM)
Sources of Savings & Capabilities

Sources of Savings:
• Material and energy saving
• Reduction in human effort in data processing
• Elimination of roughing operation

Capabilities:
• Composite dies (Benefits: material saving, desirable mech. Properties)
• Conformal cooling channels (Benefits: reduced cycle time, low warpage, high quality)
  Discrete adaptive slicing
  Gradient matrix
Hybrid Layered Manufacturing (HLM)
Case studies in 3-/5-axis

<table>
<thead>
<tr>
<th>3-Axis HLM</th>
<th>5-Axis HLM (Positional)</th>
<th>5-Axis HLM (Continuous)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic dies</td>
<td>Components with several 3-axis features in different orientations</td>
<td>Impeller</td>
</tr>
<tr>
<td>Composite Dies with conformal cooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Components without undercuts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Components with undercuts</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Indexed or Positional 5-Axis HLM
Manufacture of components with abrupt and large undercuts which can be divided into chunks converging in different directions. They are arranged in a suitable order to build.

Note that indexed or positional 5-axis machines are considerably cheaper and easier to program; often they are restricted too.
Indexed or Positional 5-Axis HLM

Case study: Al Casing

(a) A component that is manufactured in 2 settings in 3-axis machining

(b) Start with clamping the above substrate on the table

(c) Build a cylindrical piece on top of it

(d) Build a disc on top of this cylinder

(e) Build an annular cylinder around this disc

(f) Build a ring at the end of the annular cylinder

(g) Build the small projecting stud on the annular cylinder at the appropriate orientation
5-Axis HLM
5-axis HLM
Principle & Construction

“total automation” as building is still in planar layers.

Rotary axes eliminate need for support.

The table simply tilts to capture the falling droplet.

5-axis machine with a vertical spindle is used (down-hand).
5-axis HLM
Tilting to capture the droplet

- Components with high overhang difficult to build in 3-axis
- Tilt the torch/table to make the deposition undercut-free

Normal Position (Greater overhang)  Tilted Position (Overhang in-line with torch)
5-axis HLM
Additional care & constraints

- ATC operations to avoid collisions: The face mill is always present in the spindle in 3-axis HLM – it is kept about 5mm below the torch. This is not possible in 5-axis HLM due to the possibilities of collision. So, we keep a dummy holder with no protrusion in the spindle during deposition. So, tool change is used twice for each layer.

- Limiting ‘A’ axis: ‘A’ axis tilt has to be restricted to a limiting value (physically measured for the worst case) to avoid collision. When it exceeds the limit, the normal is corrected towards vertical. *(Handled during 5-axis slicing).*

- Limiting ‘C’ axis: Although ‘C’ axis can rotate infinitely, it has to be restricted to [0-360] as the earth line is connected to it *(mechanical damage! electric shock!!)*. Earthing from a non-rotating member has some resistance drop. *(Handled during post-processor)*,
5-axis HLM
Processing steps

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
<th>Axes</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Face milling</td>
<td>2.5</td>
<td>• Removes scallops</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Exposes nascent surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Ensures vertical accuracy</td>
</tr>
<tr>
<td>2.</td>
<td>Deposition of the boundary contours</td>
<td>5</td>
<td>• Realizes undercut features</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Creates a container</td>
</tr>
<tr>
<td>3.</td>
<td>Filling the interior using an appropriate area filling (contour or direction parallel)</td>
<td>2.5</td>
<td>• Bulk of deposition</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Heat management</td>
</tr>
</tbody>
</table>

Note: Even in CNC machining, 5-axis motion is used only when required. Rest of the time, it will use less axes.
A slice consists of hierarchically arranged non-intersecting loops.

For the traditional 2.5 axis RP, each loop is defined by a series of points $\bar{p}_i = [x_i \ y_i \ z]$ where $z$ is constant for the slice.
5-axis HLM
5-axis slicing

For the variable axis RP, each of these points is additionally associated with a torch vector \( \hat{t}_i = [i_i \ j_i \ k_i] \)

\[
\hat{t}_i = \hat{n}_i \times \hat{d}_i
\]

In other words, the torch vector is the normalized cross product of the normal and direction vectors.
5-axis HLM

5-axis slicing ...

Directions of normal and torch unit vectors for a triangle
5-axis HLM
Post-processing
Post-processing is the conversion of the slice data in global CL form coordinates of the machine (joint coordinates).

\[
CL = \begin{bmatrix} x_b & y_b & z_b & i & j & k \end{bmatrix}
\]

\[
H = \begin{bmatrix} x & y & z & a & c \end{bmatrix}
\]

Note: \((f_y, f_z)\) are constants defining the fulcrum of the rotary axes. \((b_x, b_y, b_z)\) are the offset of the substrate w.r.t. the table centre.
5-axis HLM
Post-processing …

\[ x = x_b \cos c - y_b \sin c - b_x \cos c + b_y \sin c + b_x \]

\[ y = x_b \cos a \sin c + y_b \cos a \cos c - z_b \sin a - b_x \cos a \sin c - b_y \cos a \cos c + b_z \sin a - f_y \cos a + f_z \sin a + f_y + f_z \]

\[ z = x_b \sin a \sin c + y_b \sin a \cos c + z_b \cos a - b_x \sin a \sin c - b_y \sin a \cos c - b_z \cos a - f_y \sin a - f_z \cos a + b_z + f_z \]

\[ a = \cos^{-1} k \]

\[ c = \tan^{-1} \left( \frac{i}{j} \right) \]

Note: If \( \gamma \) can have infinite rotation, use \( \text{atan2}(i, j) \) which returns \( \gamma \) in the range of \([-\pi, \pi]\). If it should be limited to a single rotation, \( \tan(i/j) \) will do which returns \( \gamma \) in the range of \([-\pi/2, \pi/2]\).
5-axis HLM
5-axis boundary contours deposition of a layer (Video)
5-axis HLM
2.5-axis area-filling

The direction can be chosen appropriately for various reasons:
- to achieve homogeneity
- To minimize motions
- To minimize the no. of dir. changes

Two type are:
- in-to-out (spiral out)
- out-to-in (spiral in)

Spiralling out is preferred to achieve favorable heat conduction.
5-axis HLM

2.5-axis area-filling deposition of a layer (Video)
5-axis HLM
HLM - 5-axis deposition (Video)
5-axis HLM
HLM - 5-axis machining (Video)
# 5-axis HLM

**HLM - 5-axis machining**

<table>
<thead>
<tr>
<th></th>
<th>CAD Model</th>
<th>Near-net Shape</th>
<th>Final Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing's Ti Part Built Using LAM</td>
<td><img src="image1" alt="CAD Model" /></td>
<td><img src="image2" alt="Near-net Shape" /></td>
<td><img src="image3" alt="Final Shape" /></td>
</tr>
<tr>
<td>Al Impeller Built Using HLM</td>
<td><img src="image4" alt="CAD Model" /></td>
<td><img src="image5" alt="Near-net Shape" /></td>
<td><img src="image6" alt="Final Shape" /></td>
</tr>
</tbody>
</table>
Future Plans for HLM
Expanding to other deposition methods

MIG, TIG and Laser HLMs have their own domain of applications. Therefore, we are currently developing TIG HLM thro’ local funding. Soon, we shall start Laser HLM through an Indo-UK project together with Cranfield and Nottingham universities.

<table>
<thead>
<tr>
<th>HLM Type</th>
<th>Features</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIG</td>
<td>Unified control of mass and current flows makes the process simple.</td>
<td>Medium precision features (&gt;2mm) on large parts</td>
</tr>
<tr>
<td>TIG</td>
<td>Independent control of mass and current flows makes the process very versatile. Ability to handle multiple wires/strips → FGM feasibility</td>
<td>Medium precision features (&gt;1mm) on medium parts</td>
</tr>
<tr>
<td>Laser</td>
<td>Independent control of mass and current flows makes the process very versatile. Ability to handle multiple wires/strips → FGM feasibility</td>
<td>High precision features (&gt;0.25mm) on small parts</td>
</tr>
</tbody>
</table>
The additive part of present HLM software was developed in-house using Visual C++ and OpenGL. It takes STL input. The subtractive part is done using any CAM software. The HLM algorithm is being ported to Delcam using its Application Programming Interface (API). This will have the following strategic benefits:

• We will be able to exploit the time-tested routines of offsetting and area-filling.

• We shall be able to use not only STL but smooth geometries as well.

• We need not develop post-processor as Delcam’s post-processor will do the job.

• Both additive and subtractive parts of data processing can be done on a single platform.
Conclusions
Conclusions

- HLM uses 5-axis kinematics to overcome the need for a support mechanism. 5-axis HLM is able to build complex geometries such as impeller.

- MS, tool steel and Al have been successfully used. Inconel and Ti alloys will be tried next in that order. 3-axis HLM is able to build a composite die with conformal cooling in adaptive layers.

- HLM presently uses MIG deposition. Since MIG, TIG and laser have their own domains of applications due to their complementing nature of cost and capabilities, we are expanding HLM to use these deposition head as well.

- Use of multiple wires/strips fed differentially will help realize gradient matrix.
Thank You!

K.P. Karunakaran
Professor, Mechanical Engineering
IIT Bombay, INDIA
karuna@iitb.ac.in

Till July 15:
Ecole Centrale de Nantes, FRANCE
+33-240-371636
3-Axis HLM
3-Axis HLM
Case study 1: Monolithic injection molds

Egg template of a refrigerator
(Courtesy: Godrej)
3-Axis HLM

Case study 1: Monolithic injection molds ...
3-Axis HLM
Case study 1: Monolithic injection molds...

Nearnet
As machined
After polishing and use
3-Axis HLM

Case study 1: Monolithic injection molds ...

Saving in time

37.5%

Saving in cost

22.3%
3-Axis HLM
Case study 2: Composite mold with conformal cooling

Three interesting features are:

i. Composite dies (Benefits: material saving, desirable mech. Properties)
ii. Conformal cooling channels (Benefits: reduced cycle time, low warpage, high quality)
iii. Discrete adaptive slicing
3-Axis HLM

Case study 2: Comp. mold with conformal cooling ...
3-Axis HLM
Case study 2: Comp. mold with conformal cooling ...
3-Axis HLM

Case study 2: Comp. mold with conformal cooling ...
3-Axis HLM

Case study 2: Comp. mold with conf. cooling - Benefits

1. Composite die: A case of P20/H13 tool steel (about 8-10mm) and core of mild steel:
   - Net savings in material cost
     
     |                | Price in Rs./kg |
     |----------------|-----------------|
     | P20            | M.S.            |
     | Block form     | 300             | 45              |
     | Wire form      | 500             | 70              |

   - Favorable mechanical properties: Good fatigue life due to tougher core and long tool life due to harder case.

2. Benefits of conformal cooling are (i) reduced cycle time, (ii) distortion and (iii) homogeneous matrix.

3. Discrete adaptive layers. This is a unique capability of HLM.
3-Axis HLM
Case study 2: Comp. mold with conformal cooling ...

Two views of the part Filtrum – Rear light holder of a Bajaj Bike
[Courtesy: C.R. Tooling, Mumbai]
Its punch and cavity. These monolithic injection mold was manufactured by C.R. Tooling, Mumbai recently and is presently used in a factory in Pune. We took up only the punch.
3-Axis HLM

Case study 2: Comp. mold with conformal cooling ...

Step 1: Offset the die by the machining allowance (1mm in this case). This is because we prefer not to give any the machining allowance to the HLMSoft. [Caution: Do any offsetting only in the CAD package before triangulation. It is not efficient after triangulation.]
Step 2: Split this offset die into case and core
Step 3: Using the component model, design the cooling ducts. Packages such as *MoldFlow* help in designing efficient cooling ducts. The cooling duct we designed is shown in the figure. This cooling duct is subtracted from the core of the punch.
3-Axis HLM
Case study 2: Comp. mold with conformal cooling ...
Step 4: The core of the punch with the cooling duct shown in the figure is not manufacturable using HLM since its three top horizontal surfaces do not have any support (see figure on the left side). Therefore, we shall build these with isosceles triangular cross-section rather than rectangular cross-section. These shapes are shown in the middle figure. Adding these three segments will make the core manufacturable using HLM (see figure on the right side).
Thus, for the sake of modularity of material switching and adaptive layer thicknesses, the die is split into the following 3 files and separately processed in HLMSoft without machining allowance at appropriate slice thicknesses:

1. STL-1: Case of the punch (to be made out of P20 tool steel in layer thicknesses of 1.5mm)
2. STL-2: Core of the punch (to be made out of mild steel in layer thicknesses of 1.5mm)
3. STL-3: The three triangular segments of the conformal duct (to be made out of mild steel in layer thicknesses of 0.5mm)
Fronius TPS 4000 was loaded with the P20 tool steel (1.2 mm dia solid-cored) and Fronius TPS 2700 CMT was loaded with mild steel (0.8 mm dia monolithic). The sequence of their building for each layer is as follows:

1. Switch to Fronius TPS 2700 CMT to deposit mild steel.
2. Deposit 0.5mm layer of STL-3.
3. Face mill at 0.5mm.
4. Deposit next 0.5mm layer of STL-3.
5. Face mill at next 0.5mm.
6. Deposit next 0.5mm layer of STL-3.
7. Deposit 1.5mm layer of STL-2.
8. Switch to Fronius TPS 4000 to deposit P20 tool steel.
9. Deposit 1.5mm layer of STL-1.
10. Face mill at 1.5mm.
3-Axis HLM

Case study 2: Comp. mold with conformal cooling ...
## 3-Axis HLM

Case study 2: Comp. mold with conformal cooling ...

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Cost/Unit (Rs.)</th>
<th>Cost (Rs.)</th>
<th>Value</th>
<th>Cost/Unit (Rs.)</th>
<th>Cost (Rs.)</th>
<th>Value</th>
<th>Cost/Unit (Rs.)</th>
<th>Cost (Rs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base plate</td>
<td>0.00</td>
<td>45</td>
<td>0</td>
<td>12.18</td>
<td>250</td>
<td>3045</td>
<td>11.50</td>
<td>45</td>
<td>518</td>
</tr>
<tr>
<td>MS wire</td>
<td>0.00</td>
<td>71</td>
<td>0</td>
<td>0</td>
<td>71</td>
<td>0</td>
<td>4.90</td>
<td>71</td>
<td>348</td>
</tr>
<tr>
<td>P20 wire</td>
<td>20.50</td>
<td>250</td>
<td>5125</td>
<td>1.46</td>
<td>250</td>
<td>365</td>
<td>7.32</td>
<td>520</td>
<td>3807</td>
</tr>
<tr>
<td>Data processing (hour)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near-net</td>
<td>1.00</td>
<td>400</td>
<td>400</td>
<td>0.25</td>
<td>400</td>
<td>100</td>
<td>2.00</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>Finishing</td>
<td>1.00</td>
<td>400</td>
<td>400</td>
<td>1.00</td>
<td>400</td>
<td>400</td>
<td>1.00</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Manufacture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(hour)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near-net</td>
<td>10.00</td>
<td>300</td>
<td>3000</td>
<td>1.98</td>
<td>300</td>
<td>595</td>
<td>12.54</td>
<td>400</td>
<td>5016</td>
</tr>
<tr>
<td>Finishing</td>
<td>5.00</td>
<td>300</td>
<td>1500</td>
<td>5.00</td>
<td>300</td>
<td>1500</td>
<td>5.00</td>
<td>300</td>
<td>1500</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10425</td>
<td></td>
<td>6005</td>
<td></td>
<td></td>
<td>12388</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CNC – Traditional (subtractive)  
HLM-M – Monolithic  
HLM-CC – Composite with Conformal ducts

- Monolithic die made using HLM would cost only about 60% of the traditional route.
- Composite die with conformal cooling duct will cost about 20% more than the traditionally made monolithic die.
- Costlier the die material and more complex/ sparser features, more will be the benefits.
3-Axis HLM
Case study 2: Comp. mold with conformal cooling ...

Comparison of cost

Comparison of time
3-Axis HLM
Case study 3: Monolithic Al-Si5 Propeller

- Blinding of the abrupt undercuts to be machined later.
- 3-axis HLM; planar deposition
- No support required
- Uniform layers
3-Axis HLM
Case study 3: Monolithic Al-Si5 Propeller …

Top ad bottom views
3-Axis HLM
Case study 3: Monolithic Al-Si5 Propeller …

Retain only the top surfaces. Our code is able to identify this.
Create the side walls and complete the solid which is free from undercuts.

Add eye end which will facilitate clamping in the next setting.
3-Axis HLM
Case study 3: Monolithic Al-Si5 Propeller …

Blank
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
3-Axis HLM

Case study 3: Monolithic Al-Si5 Propeller …
3-Axis HLM

Case study 3: Monolithic Al-Si5 Propeller …

Layer 12

Layer 13

Layer 14

Layer 15

Near-net shape

Side-1 finish machined
3-Axis HLM

Case study 3: Monolithic Al-Si5 Propeller …

- HLM route for this case took 47% less time than the CNC route
- A cost reduction of 43% was archived through HLM route over CNC route.
- The cost of the raw material too was observed to be 38% low in the case of HLM in spite the higher cost of the filler material over a regular block
- Costlier the material and more complex/ sparser features, more will be the benefits.
### 3-Axis HLM

**Case study 3: Monolithic Al-Si5 Propeller …**

<table>
<thead>
<tr>
<th>CNC Processing Step</th>
<th>Time (min)</th>
<th>HLM Processing Step</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC program generation rough machining</td>
<td>60</td>
<td>Data processing of the STL file</td>
<td>10</td>
</tr>
<tr>
<td>NC program generation for finish machining</td>
<td>60</td>
<td>NC program generation for finish machining</td>
<td>60</td>
</tr>
<tr>
<td>Rough machining</td>
<td>151</td>
<td>Near-net shape manufacture</td>
<td>47</td>
</tr>
<tr>
<td>Finish machining</td>
<td>60</td>
<td>Finish machining</td>
<td>60</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>331</strong></td>
<td><strong>Total</strong></td>
<td><strong>177</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CNC Processing Step</th>
<th>Cost (Rs.)</th>
<th>HLM Processing Step</th>
<th>Cost (Rs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material cost (solid block of Aluminium @ Rs 210 per kg)</td>
<td>224</td>
<td>Raw material cost (Aluminium substrate @ Rs. 210 per kg and filler wire @ Rs. 600 per kg)</td>
<td>102</td>
</tr>
<tr>
<td>NC programming cost using a package @ Rs. 400 per hour</td>
<td>800</td>
<td>Data processing cost using HLMSoft @ Rs. 400 per hour</td>
<td>467</td>
</tr>
<tr>
<td>Manufacture of near-net shape through rough machining on a 3 axis milling CNC @ Rs. 300 per hr</td>
<td>755</td>
<td>Manufacture of near-net through HLM @ Rs. 400 per hour</td>
<td>313</td>
</tr>
<tr>
<td>Finish machining on a 3 axis milling CNC @ Rs. 300 per hour</td>
<td>300</td>
<td>Finish machining on a 3 axis milling CNC @ Rs. 300 per hour</td>
<td>300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2,079</strong></td>
<td><strong>Total</strong></td>
<td><strong>1,182</strong></td>
</tr>
</tbody>
</table>
3-Axis HLM
Case study 3: Monolithic Al-Si5 Propeller ...

- HLM route for this case took 47% less time than the CNC route.
- A cost reduction of 43% was archived through HLM route over CNC route.
- The cost of the raw material too was observed to be 38% low in the case of HLM in spite the higher cost of the filler material over a regular block.
- Costlier the material and more complex/ sparser features, more will be the benefits.
This is a supporting structure of our SOM machine.
3-Axis HLM

Case study 4: Monolithic tall Al Part ...

Various phases in the manufacture
3-Axis HLM
Case study 4: Monolithic tall Al Part

### Cost Saving

- **Cost Saving = 20%**

### Time Saving

- **Time Saving = 29%**

<table>
<thead>
<tr>
<th>Processing Step</th>
<th>Cost (Rs)</th>
<th>CNC</th>
<th>HLM</th>
<th>Processing Step</th>
<th>Time (mins)</th>
<th>CNC</th>
<th>HLM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Material</td>
<td>1459</td>
<td>889</td>
<td></td>
<td>Near-net shape paths</td>
<td>224</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>Data Processing</td>
<td>400</td>
<td>233</td>
<td></td>
<td>Finishing paths</td>
<td>800</td>
<td>467</td>
<td></td>
</tr>
<tr>
<td>Near-net Shape</td>
<td>2440</td>
<td>2282</td>
<td></td>
<td>Near-net shape manufacture</td>
<td>755</td>
<td>313</td>
<td></td>
</tr>
<tr>
<td>Finish Machining</td>
<td>345</td>
<td>291</td>
<td></td>
<td>Finish Machining</td>
<td>300</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4644</strong></td>
<td></td>
<td></td>
<td><strong>Total</strong></td>
<td><strong>2079</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Processing Step**

- Near-net shape paths: 224 mins (CNC) vs. 102 mins (HLM), **Time Saving = 57%**
- Finishing paths: 800 mins (CNC) vs. 467 mins (HLM), **Time Saving = 41%**
- Near-net shape manufacture: 755 mins (CNC) vs. 313 mins (HLM), **Time Saving = 58%**
- Finish Machining: 300 mins (CNC) vs. 300 mins (HLM), **Time Saving = 0%**

**Graphs:**

- Bar graph showing cost savings across processing steps.
- Bar graph showing time savings across processing steps.