Finish Machining of Direct Metal Additive Manufactured Parts

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Medical Applications
- Custom Implants
- Novel Implants
- Regenerative Medicine

New Material Development for Direct Metal Fabrication
- Medical
- Aerospace
- Electronics

Finishing of Direct Metal Parts

Logistical issues facing the AM revolution
- New Design Opportunities
- Weight reduction
- More complex geometries

Design For Additive Manufacturing
Polymer Based Additive Processes

SLA 250  Dimension  Connex 350  Z Corp

BFB 3000  RapMan  MakerBot  Fab@Home  Cube
Printing Tissues:

- WFIRM-NCSU scaffold fabrication project:
  - Scaffold design characterization
    - Scaffolds with micro-scale design features (feature sizes ≤ 100µm)
  - 3D Bioplotting process engineering
    - Investigation of the repeatability and reliability of 3D Bioplotting using biopolymers and hydrogels for direct organ printing

- Materials
- Vascularization
- Production Consistency
Direct Metal Manufacturing

2003

2007

Biomedical

Aerospace

2013
Need for Finish Machining

• Most parts produced via Direct Metal Additive Manufacturing processes need finishing for “real” applications
• Traditional CNC-machining is currently too labor intensive for finishing of small lots
• An automated process is needed to make AM more productive and more economically feasible
CNC-RP Background

- Developed by Drs. Matt Frank, Rick Wysk, and Sanjay Joshi at Penn State
- CNC-Rapid Prototyping
- ‘CAD-to-produce’ AM-like approach
- Layer-based island milling
- 4-axis CNC setup
- Sacrificial fixturing
  - Material and machining conditions
  - Visibility analysis
  - Minimum amount of rotational indexing with maximum facet visibility
CNC-RP

- CNC-RP stages based on machining parameters and tooling:
  - Hogging (*material clearance*)
  - Roughing (*feature-dependent*)
  - Finishing (*feature-dependent*)

- Attributes of CNC-RP
  - No manual tool path generation
  - Geometric limitations
  - Loss of material as scrap and chips
  - Machining of superalloys
    - Lower machinability
    - Long machining times
    - Tooling cost
HYBRID APPROACH
Hybrid Approach to AM

- ‘Global’ hybrid approach applicable to all AM processes
- Independent of AM processing conditions
  - Could be used for cast parts as well
- Goal is a fully automatic system from CAD-design to final part
- Software system that guides the process
  - Process planning from step one
  - Seamless transition from step to step
- Designed to accommodate future finishing steps
- Adaptable to all AM processes without modifications to existing equipment
- Will work with any 4-axis capable CNC-machine
Hybrid Schematics

- Incorporating CNC-RP fixtures prior to AM processing (e.g. EBM)
Process Flow

- Flow of information and material across AIMS

### Start → CAD file → Process Planning → AM stage

- **CAD file**
  - Part design and material
  - File formats: STL, AMF, STEP, etc.
  - Critical features → Tolerance and Surface roughness callout

- **Process Planning**
  - Visibility analysis
  - Fixture design and location
  - AM specific → Shrinkage, surface roughness, build volume, orientation, support structures, etc.
  - Maximum deviation analysis
  - Surface overgrowth
  - AM process files
  - NC Toolpath → Tool library

- **AM stage**
  - Set-up build → Plate, powder, etc.
  - Calibrate AM machine → Laser, EBM, etc.
  - Start build
  - Retrieve build upon completion
  - Remove support structures for overhanging edges

### Start → Cut-off → CNC-RP

- **Cut-off**
  - Saw-off sacrificial fixtures
  - Manual finishing of the fixture marks in the part
  - Measure and Record data → Part accuracy, surface roughness, machining time and total production time

- **CNC-RP**
  - Qualify tool lengths and diameters
  - Qualify machine → Axis of rotation
  - Fixure AM-part in CNC-RP
  - Probe to re-qualify part location after machining each rotation
  - Laser scan to collect cloud point data of part after fixturing and during rotation
  - NC toolpath modification based on requalification with probe and/or with laser scanned information

**AIMS Process Flow**
Current Studies

• Incorporating CNC-RP fixtures prior to AM processing

• Optimizing the design of the fixture geometries
  • Minimize impact of process inaccuracies
  • Reduce deflection
  • Maximize tool access
  • Minimize AM process impact
Ideal vs. Actual setup

- Large disparity between CNC-RP (from a stock) and AM

- Generated toolpath is not related to actual set-up observed
- Attributed to:
  - **Surface roughness of the fixturing features** (EBM $R_a \sim 275-300 \, \mu m$)
  - **Geometrical accuracy of the fixturing features** (shrinkage characteristics)
Ideal vs. Actual setup

• CNC-RP vs. Hybrid fixturing

• Effect of Hybrid fixturing
SCANNING TO LOCATE PART
Process

1. Scan part in machine
2. Locate captured data in machine coordinate system
3. Merge scans: generate model of part in machine
4. Compare model to nominal (ideal) position, orientation, and form
5. Generate toolpaths for removal of support structures
6. Generate offsets for machining
7. Modify toolpath to compensate for deviation in form
8. Perform next set of machining operations
9. Re-scan and repeat until part successfully completed
Initial results – scanned and nominal parts
Initial results – scanned cloud aligned to nominal location using ICP algorithm
NextEngine Scanner

Dual Approach

- Scanner is used to capture the existing volume
  - Part
  - Support
- Scanner is used to orient the part
- CNC-probing capability used to acquire the necessary resolution
OPTIMIZE SACRIFICIAL SUPPORTS
Methodology

1. Start
2. Create cutting force model
3. Calculate maximum cutting force
4. Create or input Geometric model
5. Add boundary conditions and Load cutting forces
6. Calculate deformation
7. Check if deformation is within permissible limits
   - Yes: Use NC code for CNC RP machining
   - No: Modify support dimensions using optimization toolbox
8. Generate toolpath and sacrificial supports using CNC RP in Mastercam
9. End
Calculating toolpath and dimensions of sacrificial supports

- MasterCam exports tool path
- MasterCam exports the sacrificial supports optimized for CNC-RP
Cutting force model

- Calculating maximum cutting forces
- Dynamic analysis
- Validating models using physical experiments

\[
F_x(\phi) = \frac{K_f R}{4 \tan \beta} \left[ \cos 2\phi_j + K_r (2\phi_j(z) - \sin 2\phi_j(z)) \right] z_{ij}(\phi),
\]
\[
F_y(\phi) = -\frac{K_f R}{4 \tan \beta} \left[ (2\phi_j(z) - \sin 2\phi_j(z)) + K_r \cos 2\phi_j(z) \right] z_{ij}(\phi),
\]
\[
F_z(\phi) = -\frac{K_a K_f R}{\tan \beta} \left[ \cos \phi_j(z) \right] z_{ij}(\phi),
\]
Finite Element Model

- Using maximum cutting force to calculate deflection
- Using structural optimization to adjust supports
- Validation using physical experiments
Hybrid Schematics

- Incorporating CNC-RP fixtures prior to AM processing (e.g. EBM)
Future Research

• Development of overall architecture
• Follow-on processing steps
  – Grinding
  – Polishing
  – Electrochemical Machining
• Using the same set-up features
• Add modules to the overall architecture
Questions: