ROBOTIC HYBRID (AM-ME, SM) MULTIAXIS MANUFACTURING

Tadeusz Kosmal, Dr. Joseph Kubalak (Advisor), Dr. Christopher Williams (Advisor)
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Abstract

Polymers and composites have desirable mechanical properties, ranging from corrosion resistance to remarkably higher strength to weight ratios when compared to metals. Material Extrusion (ME) Additive Manufacturing (AM) using robotic platforms, provides additional flexibility to produce high-performance parts unattainable by conventional 3-Axis, gantry style machines. The high manipulability of robotics coupled with the asymmetric and unorthodox design capability of AM allows for non-trivial, high-performance construction using polymer and composites using planar or multi-axis construction. While AM-ME can enable realization of complex geometries from its layered approach to fabrication, it is an inherently inaccurate process due to inter/intralayer voids and large layer thickness which result in porous and rough parts, especially prominent in large-scale, robotic 3D printing. This work has demonstrated the workflow and process for creating a hybrid AM-ME/Subtractive Manufacturing (SM) process to remove surface defects limiting the usefulness of robotically formed AM-ME parts. While a hybrid robotic AM-ME/SM process is limited by the stiffness and vibration of robotic platforms and polymer parts, multi-axis SM post processing removes surface irregularities, and allows for mid-print surface preparation yielding greater mechanical performance.

Introduction and Motivation

Polymers and composites have desirable mechanical properties, ranging from corrosion resistance to remarkably higher strength to weight ratios when compared to metals. Material Extrusion (ME) Additive Manufacturing (AM) using robotic platforms, provides additional flexibility to produce high-performance parts unattainable by conventional 3-Axis, gantry style machines. The high manipulability of robotics coupled with the asymmetric and unorthodox design capability of AM allows for non-trivial, high-performance construction using polymer and composites using planar or multi-axis construction, where 3D printing layer can be conformed to the geometry of the part, seen in Figure 1.

While AM-ME can enable realization of complex geometries from its layered approach to fabrication, it is an inherently inaccurate process due to inter/intralayer voids and large layer thickness which result in porous and rough parts.

Figure 1. An AM-ME multi-axis print of a propeller part.

Surface artifacts are especially prominent in large-scale, robotic 3D printing platforms due to vibration in robot joint structure and unmatched process and robot kinematic profiles. Figure 2 shows the difference in surface roughness between a 3-Axis and Robotic AM-ME 3D Print.

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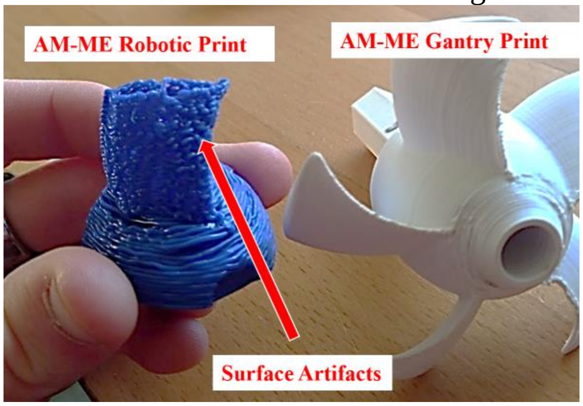

Figure 2. Difference in surface finish between a multi-axis and a planar AM-ME propeller.

The prevalence of surface artifacts limits the usefulness of parts due to aesthetics, surface roughness, and increased likelihood of cracking. This research specifically looks to increase the fidelity of planar and non-planar robotic AM-ME through incorporation of Subtractive Manufacturing (SM). SM allows imperfections in ME to be removed, and parts to be machined to exact dimensions, seen in Figure 3.

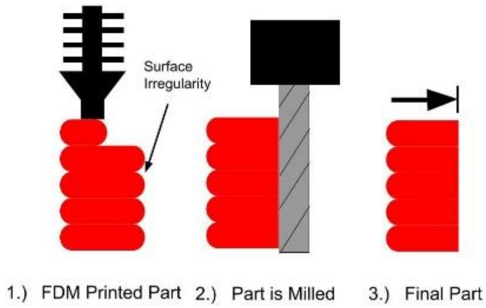

Figure 3. A schematic of an AM-ME print being surfaced finished using SM.

Integration of AM and SM creates an overall hybrid autonomous process. A hybrid process enables parts made of polymers or composites with the aforementioned tolerance vulnerabilities, to be more broadly used in aerospace applications.

Previous Work

Despite AM-ME's dimensional drawbacks, multi-axis ME is especially desirable in aerospace applications as deposition can be optimized according to loading conditions, enabling lighter, high-performance parts[1]. Applications range from 3D Printed drones needing tight tolerances/fits for non-printed hardware (e.g., motors, electronics), wind tunnel aircraft models requiring low surface roughness, to manufacturing extraterrestrial infrastructure.

SM (e.g., Milling) allows removal of these surface irregularities by cutting the surface of the part into a uniform exterior. Li, Haghighi, and Yang demonstrated a similar robotic manufacturing process, milling the exterior of printed parts, achieving better surface roughness comparable to extruded polymer parts[2]. However, this research can be expanded upon as the AM process is purely planar/curved planar, containing simplistic geometry not enabling construction of optimized, high-performance parts. The SM process is likewise geometrically simplistic - not only is it a purely planar process, but it did not perform differing machining strategies (i.e., swarfs) to minimize surface roughness. This research elaborates on Li, Haghighi, and Yang's work by utilizing the full manipulability of a robotic system to enable multi-planar/axis tool pathing in SM/AM operations.

Methodology

Before beginning hybrid AM/SM operations, process parameters for the combined process relating to substrate, cutting rates, and material needed to be evaluated to determine the viability of hybrid operations on an ABB IRB 1200 robotic platform.

To perform initial tests, a Dremel running at 15,000 rpm was used to test the adhesion of printed parts under cutting loads. Cutting was placed to maximize the shear force on the interface between the printed part and the substrate, seen in Figure 4, to test work holding during SM operations. Using blue tape and a 0.2mm initial layer height with over extrusion, cutting forces greater than 500N were held without separation of the printed part.

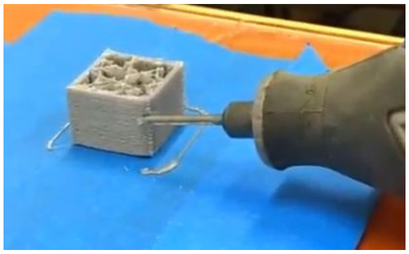

Figure 4. Initial cutting tests maximizing the shear force between substrate and printed part.

After completing initial tests, an SM End-Effector (EE) was designed for the robotic arm (AM EE already developed), seen in Figure 5. The SM EE features a quick-change tool, allowing rapid swapping between AM and SM processes. The SM EE frame was placed perpendicular to joint 6 of the robotic arm to allow undercutting, and favor robot joint positions avoiding robotic singularities to increase flexibility and safety respectively.

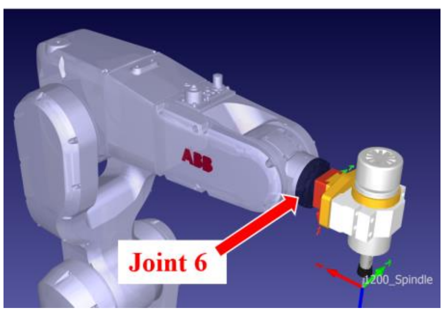

Figure 5. Designed SM end-effector.

With a toolhead and process parameters, pathing for SM and ME operations were created for planar and multi-axis digital manufacturing instructions. Planar instructions were formulated in SuperSlic3r, an open-source 3D printer slicer, while multi-axis operations were created in Autodesk Fusion 360. Fusion 360's swarf operation was used to produce multi-axis SM operations. To create multi-axis AM-ME paths, Fusion 360's wire Direct-Energy-Deposition (DED) path planner was tailored to the AM-ME process, generating surface conformal construction, seen in Figure 6.

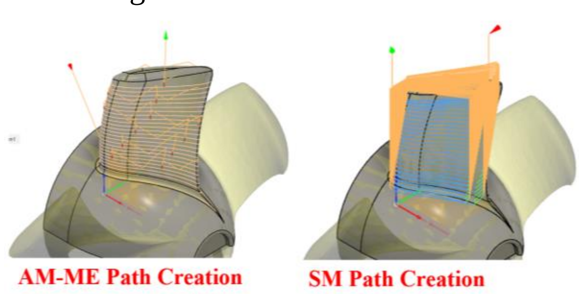

Figure 6. Multi-Axis AM ME and SM paths created in Fusion 360.

To confirm the robotic reachability of created paths, RoboDK, a robotic simulator, was used. RoboK provided a critical safety measure to check that robot joint limits were not exceeded, and no collisions occurred during fabrication. Figure 7 shows the simulation of developed AM-ME and SM.

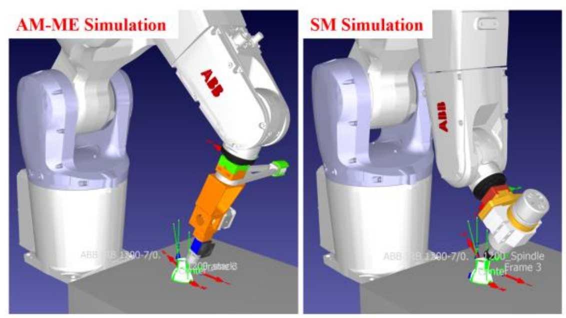

Figure 7. Multi-Axis AM ME and SM paths created in Fusion 360.

Results

Utilizing the workflow through Fusion 360 and RoboDK, paths were tested on functional parts including a drone chassis requiring tight tolerances for inserted electronics and a propeller fin necessitating a smooth surface finish.

When testing hybrid manufacturing on a drone chassis, thin walls were milled using a single flute end-mill, shown in Figure 8. Despite low feed-per-tooth, high vibration was observed due to chatter between the printed part and the end mill. This indicates a low overall stiffness in the printed structure (typical of polymers) as well as the EE. While the length of the tool can be shortened to minimize deflection, this ultimately limits the ability of the robot to reach surface finish tight spaces and features.

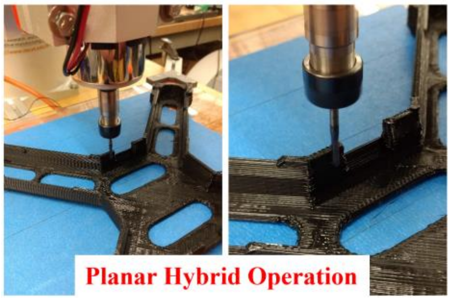

Figure 8. SM operation removing surface irregularities in planar drone chassis.

Despite chatter, the finishing operation was able to remove surface irregularities, increasing the overall external feature tolerance from ±.179mm to ±.083mm. Building upon this success, a hybrid multi-axis construction process was conducted on the propeller part, seen in Figure 9.

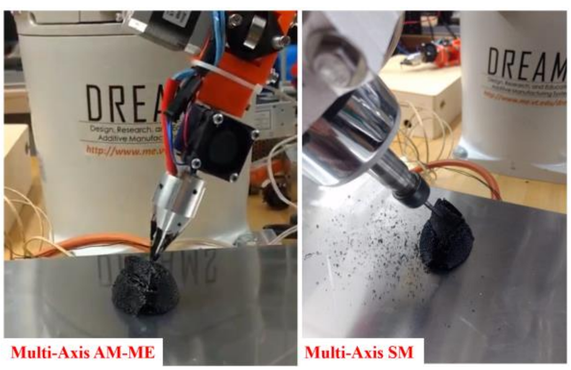

Figure 9. Multi-Axis AM/SM operation on a propeller fin part.

The multi-axis fin also demonstrated chatter throughout the print. Still, better surface roughness was achieved than the original part, allowing smoothing on external features. However, during the printing process failure occurred at the interface between a planar and non-planar layer, due to dimensional instability between the two interfaces, leading to poor interlayer adhesion. To counteract this phenomenon, the strength of non-surface milled, and surface milled layer interfaces were tested using ASTM standard 638D, displayed in Figure 10. These samples were created planarly for simplicity and to eliminate confounding variables in a multi-axis process.

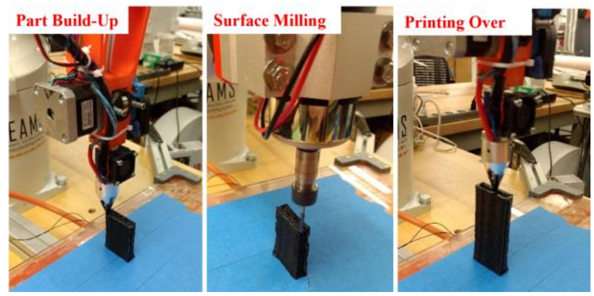

Figure 10. Images of fabrication process with and without SM surface preparation.

Samples without surface preparation featured a higher ultimate tensile strength of 1,189N, while samples with surface preparation failed at 998N, showing minimal deviation in ultimate strength. Despite a higher ultimate tensile strength, the surface prepared sample featured higher ductility, straining at maximum to 0.1 mm/mm, seen in Figure 11.

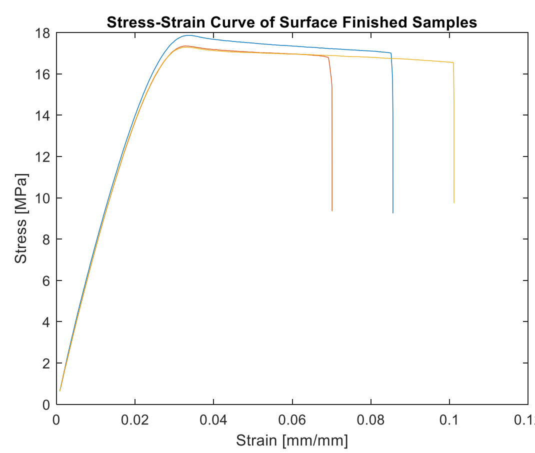

Figure 11. Stress-Strain Curve of surface finished samples, showing higher ductility.

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Comparatively, non-surface prepared samples showed significantly lower ductility, only straining to 0.04mm/mm at failure.

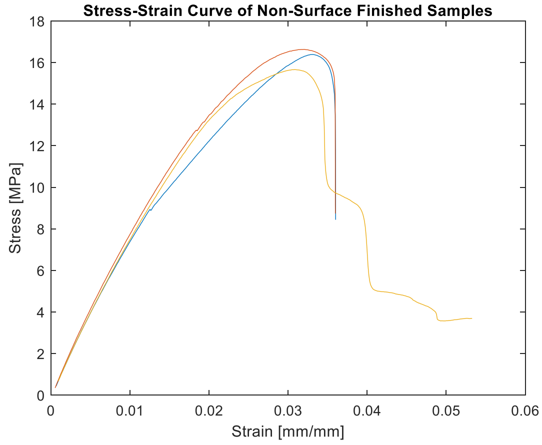

Figure 12. Stress-Strain Curve of surface finished samples, with higher ultimate tensile strength.

The significant difference in failure is likely due to better surface adhesion in the prepared sample set, leading to greater elastic performance across loading. Conversely, the higher ultimate strength and the abrupt failure mechanism in non-prepared samples is likely due do surface irregularities still present. Furthermore, the inherently destructive SM process induces vibration, cracking, etc. into the sample, reducing its ultimate tensile strength performance.

Conclusions and Future Work

This work has demonstrated the workflow and process for creating a hybrid AM-ME/SM process to overcome surface defects limiting the usefulness of robotically formed AM-ME parts. After creating fabrication paths in Fusion360, and simulation in RoboDK, higher tolerance parts can be formed in an autonomous fabrication process. While the fabrication process is limited by the stiffness and vibration of robotic platforms and polymer parts, multi-axis SM post processing removes surface irregularities, and allows for mid-print surface preparation yielding greater mechanical performance.

Despite this success, future work still needs to be completed to allow for greater autonomy during the pathing process and integrate methods to optimize pathing and process operations according to expected mechanical properties. By integrating information directly mechanical performance directly into the manufacturing pathing process, custom, tailored instructions can be created that maximize end product surface finish, dimensional tolerance, production time, mechanical performance, etc.

This empowers the use of polymers and composites with desirable mechanical properties to be employed for the future of aerospace and aviation construction.

Acknowledgements

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References

[1] Kubalak, Joseph & Wicks, Alfred & Williams, Christopher. (2018). Exploring multi-axis material extrusion additive manufacturing for improving mechanical properties of printed parts. Rapid Prototyping Journal. 25. 10.1108/RPJ-02-2018-0035.

[2] Lin Li, Azadeh Haghighi, Yiran Yang, A novel 6-axis hybrid additive-subtractive manufacturing process: Design and case studies, Journal of Manufacturing Processes,Volume 33,2018,Pages 150-160,ISSN 1526-6125, https://doi.org/10.1016/j.jmapro.2018.05.008. (http://www.sciencedirect.com/science/article/pii/S1526612518304602)

[3] Kubalak, Joseph & Wicks, Alfred & Williams, Christopher. (2017). Using multi-axis material extrusion to improve mechanical properties through surface reinforcement. Virtual and Physical Prototyping. 13. 1-7. 10.1080/17452759.2017.1392686.

[4] Pămărac, R. G., & Petruse, R. E. (2018). Study Regarding the Optimal Milling Parameters for Finishing 3D Printed Parts from ABS and PLA Materials, *ACTA Universitatis Cibiniensis, 70*(1), 66-72. doi: https://doi.org/10.2478/aucts-2018-0009