Advanced Development and Fabrication at APL: Machines, Components, and Processes

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ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (APL) solves complex research, engineering, and analytical problems that present critical challenges to our nation. Its work requires collaboration across a broad realm of scientific domains and technologies, including manufacturing. APL has established modern fabrication techniques and processes for real-world applications, enabling fabrication of components for a diverse set of systems operating from the depths of the oceans to the farthest parts of the solar system. APL delivers high-quality, cutting-edge hardware by pairing state-of-the-art equipment with knowledgeable manufacturing personnel who directly interact with engineers, designers, and research scientists to achieve creative solutions. This synergy allows for rapid iteration and swift system integration. To highlight the impact of this approach, this article describes a few of APL's critical manufacturing contributions: (1) the rapid redesign of components for the Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO), the lone instrument in the Double Asteroid Redirection Test (DART) payload; (2) the close collaboration of engineers, scientists, and fabricators on the Boundary Layer Transition (BOLT) hypersonic flight experiment; (3) the advantages of multiaxis turning for the Interstellar Mapping and Acceleration Probe (IMAP) feed horn; and (4) the use of additive manufacturing to produce novel solutions for fabricating the shielding components for instruments on the Europa Clipper and Martian Moons eXploration missions.

INTRODUCTION

Fabrication has been one of APL's core capabilities since its inception. The Lab continues to maintain the resources, facilities, and expertise to fabricate mechanical parts for complex systems that ultimately travel to the deepest depths of the ocean, the highest points in our atmosphere, and the outer reaches of space. These systems' unique missions, operating environments, and performance requirements drive quests for ever-increasing tailored functionality, lighter weights, highly organic and often non-Cartesian designs, and advanced materials. This article offers a few examples highlighting how APL manufacturing experts collaborate with engineers, designers, and research scientists and leverage advanced machining equipment and capabilities to achieve some of these goals. Related advancements in design, analysis, and programming facilitate a collaborative relationship among engineers, designers, and fabricators, accelerating the maturation of ideas into designs and ultimately functional hardware. Designs that used to be limited by manufacturing constraints such as three-axis control are now the beneficiary of more advanced fabrication capabilities, such as live tooling with five-axis control. Similarly, additive manufacturing is disrupting the industry by expanding the breadth of what can be fabricated. The impact of additive manufacturing will be increasingly profound as this technology leads a paradigm shift in the production of critical hardware.

This article describes APL's critical manufacturing contributions to four recent programs: (1) the Double Asteroid Redirection Test (DART); (2) the Boundary Layer Transition (BOLT) hypersonic flight experiment; (3) the Interstellar Mapping and Acceleration Probe (IMAP); and (4) the Europa Clipper and Martian Moons eXploration (MMX).

RAPID REDESIGN AND FABRICATION FOR NASA'S DART MISSION

NASA's DART[1] was the world's first planetary defense test mission. APL built and operated the DART spacecraft and managed the DART mission for NASA's Planetary Defense Coordination Office as a project of the agency's Planetary Missions Program Office. As the spacecraft was being prepared for its November 2021 launch, issues with the mirror assembly on its single instrument, the Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO), were discovered during vibration testing. The camera's mirror sustained damage because the hanger it was bonded to was not flexible enough to withstand the vibrations that would occur during launch. Engineers from APL collaborated with NASA Goddard Space Flight Center engineers and determined that an undercut on the mounting surfaces would provide the required flexibility, but they were unsure what was possible within the short time frame before the launch. Many discussions among engineers and fabricators culminated in a solution: a custom undercut tool. The fabrication team designed a four-flute form keyseat cutter (Figure 1), and a custom tooling company manufactured it according to the design specifications. Using this tool, the fabricator was able to modify the hanger so that it could correctly mount the mirror.

The process of fabricating the flexible hanger involved many steps. The material for the part, a nickel-iron alloy, offers thermal expansion and good strength but is difficult to machine. Therefore, all machining was completed on a five-axis milling machine whose flexible machining platform allows for five-sided machining. The first step was to rough-machine the part within 2.0 mm (0.08 of an inch) of the finished dimensions so that it could be heat treated. This additional surface material allowed for some movement during the stress-relieving process. APL material scientists identified the proper processes for heat treating the part: the part was annealed at 830°C (1,526°F) for 1 h in a furnace, then allowed to cool to room temperature in the furnace at a rate of less than 90°C per hour. This process minimized thermal expansion and maximized stability. After the roughed part was heat treated, it was held in a fixture with a set of hard jaws, shown in Figure 2. Most of the part was machined while being held by these jaws. Then the part was flipped over and finished while being held by a set of soft jaws. After final machining, the part was inspected to ensure accuracy and precision of all dimensions. Finally, it were heat treated again, this time aged at 93°C for 48 h.

The final hardware was delivered 16 calendar days after the final design was agreed upon, after more than 50 test specimens were produced to enable verification of the design before final assembly. Because of this rapid deployment, the DRACO team was able to reassemble the mirror and hanger and pass vibration testing,

Figure 1. The custom four-flute form keyseat cutter used to modify the mirror hanger on DART's DRACO instrument. To prevent damage to DRACO's mirror during launch, APL's fabrication team collaborated with the engineering team to design a custom tool that was used to modify the mirror's hanger to maximize its flexibility.

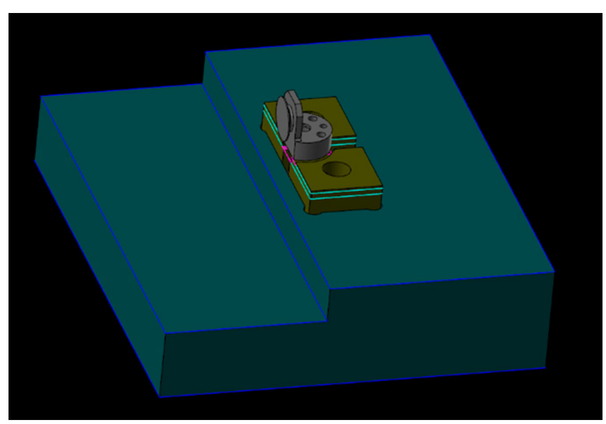

Figure 2. A model of the fixture that held the part for keyseat machining. The hard jaws (small squares) held the part (shown between the jaws) in place.

Figure 3. Before (left) and after (right) of the DRACO mirror hanger. The rapid deployment of the redesigned part allowed the spacecraft to pass vibration testing and maintain its scheduled launch date.

allowing the DART team to meet its new launch period for the mission. Figure 3 shows the original part and the final part after the design changes.

FABRICATION FOR THE BOLT FLIGHT EXPERIMENT

The BOLT flight experiment, a collaboration among academia, government, and industry, aims to further understanding of boundary layer transition—a critical phenomenon affecting hypersonic vehicle design.[2] In addition to the partnerships outside of APL, this program required a long and in-depth collaboration among APL research scientists, engineers, and machinists. The fabrication team's first task for this program was to build a 1/3-scale model out of aluminum and polyether ether ketone (PEEK), a plastic-type material, for use in wind-tunnel testing. The machinists and engineers discussed tolerances, instrumentation paths, mounting, and scheduling. This model had to have close tolerances to accurately represent a full-scale nose tip. Internal paths for instruments and the mounting of the model to the wind-tunnel mounting structure were critical considerations. And because wind-tunnel time must be scheduled in advance, on-time delivery was also paramount.

The machining was completed on a five-axis milling machine with a highly versatile range of motions and liner guides for greater accuracy. Fabrication of the small-scale model, with its complex shapes and material type, presented many challenges. PEEK tends to relieve itself while being machined, causing it to warp and move, making it difficult to assemble the components and post-machine them to hold the necessary tolerances (Figure 4) while maintaining their shape. The model was delivered on time, and the wind-tunnel tests were completed. The model was later displayed during the Smithsonian National Museum of American History's 2018 Military Invention Day.[3]

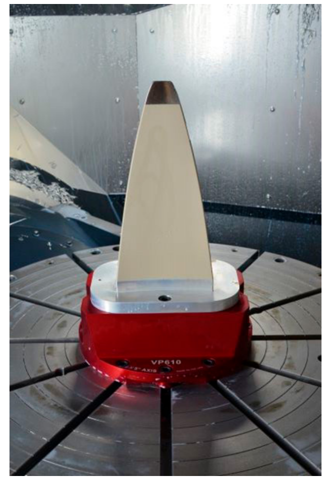

Figure 4. The 1/3-scale model of BOLT. Fabricated out of aluminum and PEEK, a plastic-type material, the model had to achieve close tolerances and on-time delivery.

After the success of the 1/3-scale model, the focus turned to modeling a full-size flight vehicle. The effort began with a kickoff meeting involving sponsors, scientists, engineers, designers, and machinists. Sponsors specifically requested that machinists attend the meeting to provide input on the manufacturability of certain features in order to avoid potential pitfalls in the fabrication process. The machinists advised adding tooling features that would ease workholding concerns and expedite manufacturing. The final full-scale model comprised a molybdenum TZM (TZM is an alloy of molybdenum, titanium, and zirconium) nose tip, a 316L stainless steel midsection, an aft end consisting of four interconnected pieces of 6061 aluminum, and, finally, four additively manufactured fairings on the back. Each material presented its own challenges during machining.

TZM is a refractory alloy whose characteristics make it difficult to machine. The material tends to tear while cutting, rather than shear, which leads to poor surface finishes, and it is abrasive to the point of wearing flats on tungsten carbide end mills while it is being cut. By using high-end coated end mills with the rigidity and precision of the five-axis milling machine, coupled with new cutting strategies offered by advanced programming software, machinists were able to efficiently process the TZM. New dynamic cutting paths enabled the TZM to be machined at a rate of more than 80 in. per minute and at a cut depth of 0.75 in.—results that were unheard of just a few years ago. Uncoated carbide tooling was used to achieve the fine surface finish required on the nose tip (Figure 5). The micro-radius on the flute generated by the coating contributed to the shearing factor, which in turn affects the surface finish. In this case, the coatings that usually extend tool life during heavy roughing were a detriment during finishing.

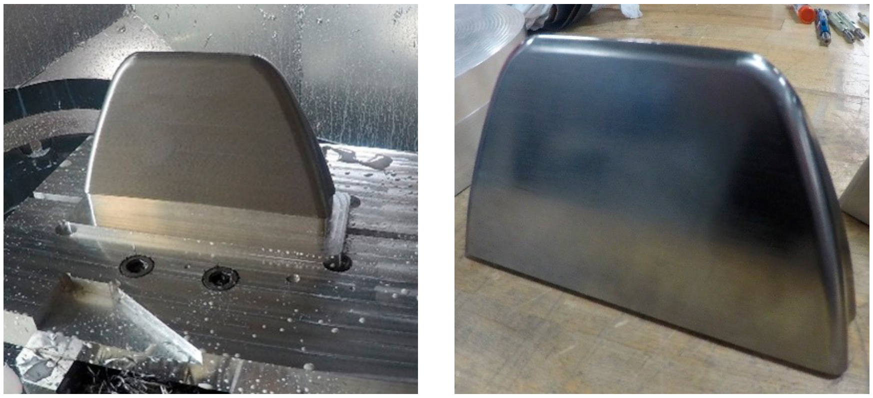

Figure 5. The TZM nose tip for BOLT. Left, the part just after the roughing operation in the machine. Right, the part after being finished and taken out of the machine.

The aft end of the assembly posed some of the greatest challenges, not because of its material but because of its shape. The four parts that made up the aft end required precise fitment (Figure 6) to avoid any unwanted steps between the parts that could affect flight or data collection. Although all pieces needed fixturing, these pieces especially required complicated custom fixturing so they could be held during machining. Modular workholding enables the machinist to pull vises or fixtures out of the machine and relocate them precisely, within 0.001 in. or closer to their previous location, to continue machining. Modular workholding systems increase flexibility and quality and speed up collaboration since the machinist can take the parts, the vise, and the fixture out of the machine with the parts still attached. The entire setup can then be given to inspection teams to check or can be taken to meetings with engineers to discuss features, mistakes, or changes, and it can then be put back into the machine for further machining. This ability was critical for the BOLT assembly, which required several skim cuts and test fits to achieve the necessary fitment. Without the precision and repeatability of the modular workholding system, fabricating these parts would have been extremely complicated and difficult.

On the other end of the tooling spectrum from the TZM, aft-end parts were cut using high-performance cutters for aluminum. The same dynamic toolpaths used for the nose tip enabled cuts at a rate of more than 400 in. per minute in aluminum. The ability to machine so quickly allowed the team to quickly turn around this highly complicated hardware. The assembly contained a few hundred instrumentation holes of various types (Figure 7). Many of these holes required deep drilling in diameters as small as 0.0625 in. With the holes all normal to the outside contour, they can only be achieved through the use of multiaxis machining.

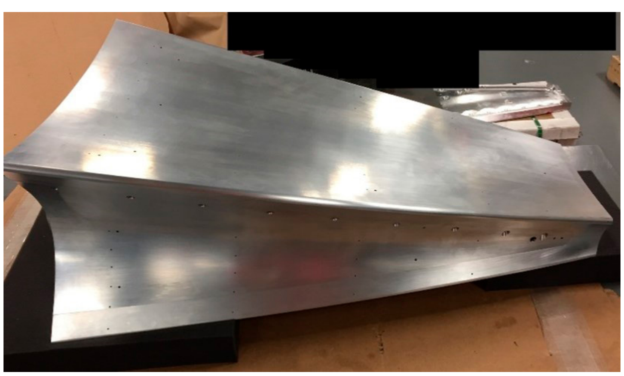

Figure 6. Precise fitment between panels for the BOLT assembly. The four parts that made up the aft end required precise fitment to avoid any unwanted steps between the parts that could affect flight or data collection.

Figure 7. BOLT aft-end assembly. Top, partially assembled BOLT aft-end assembly. Bottom, complex internal structure and instrumentation holes.

Figure 8. BOLT fairings. The fairings were additively manufactured and then post-machined.

Bolted to the back of the aft section were four fairings that were produced using metal additive powder bed technology. The fairings would have been difficult to produce using subtractive machining. Therefore, they were made of a powder-based material and post-machined to finish the critical connection surfaces (Figure 8). The machinist collaborated with the additive manufacturing team to determine where material should be left for post-machining after the additive fabrication process. In a process that is not typical of APL builds, the machinist spent many hours painstakingly gluing in and hand-filing hundreds of sensors to perfectly match the contour of the machined assembly, as well as routing and marking wires for later integration.

This collaboration continues today: BOLT 1B is being fabricated at the time of this writing, and the program's engineers and scientists continue to work closely with machinists on the next iteration of hardware.

Figure 9. IMAP medium-gain antenna feed horn. To create the grooves on the inside walls, this part was fabricated using a custom groove tool on an advanced multiaxis turning machine.

IMAP FEED HORN FABRICATION

The advantages of multiaxis machining can truly be maximized when engineers are able to use these capabilities to their advantage during the design phase. This was evident in the design of the low-gain and medium-gain antennae for IMAP, a NASA mission to investigate the heliosphere, the space filled with plasma from the Sun that envelops all the planets of the solar system.

The biggest design challenge with IMAP's medium-gain antenna was the internal geometry of the feed horn (Figure 9). Because the grooves on the inside walls are taller than most tools will reach, this part had to be machined on an advanced multiaxis turning machine. Turning and milling at the same time obviates the need to handle components multiple times, reducing the probability of a mistake. The machinist worked with a tooling vendor to determine the maximum tool diameter that would fit inside of the inner bores and be able

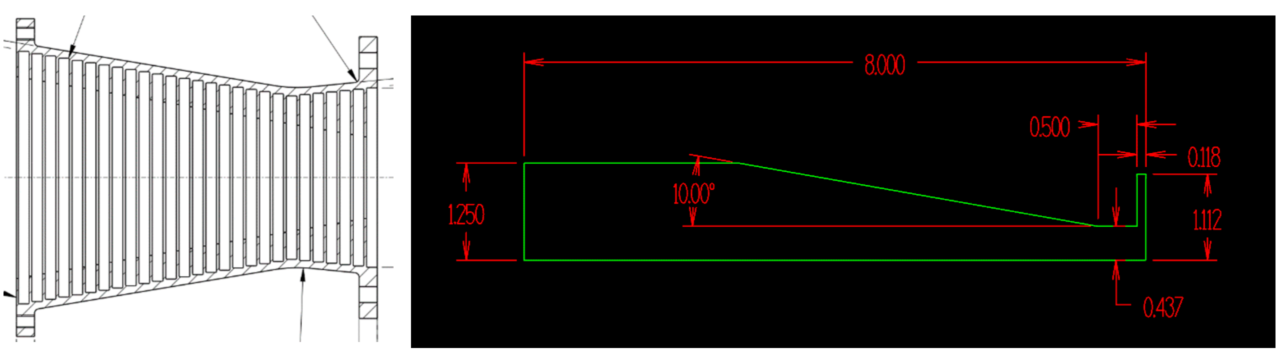

Figure 10. Computer-aided design (CAD) models for the IMAP custom grooving tool.

to groove the requested profile. The grooves were about 0.140 in. wide with 0.035 in. walls in between. The tallest grooves were 0.700 in. from the internal bore. The challenge was fitting a tool through a 1.130-in. hole, leaving a ~7/16-in.-diameter tool shank to go 5 in. deep into the part. The machinist drew up a custom groove tool, shown in Figure 10, which used the internal angle of the bores to obtain a good finish on the deep, thin-walled grooves. Collaboration between designers and machinists, along with new machining technology and the ability to work with tooling partners, made fabrication of the feed horn possible. This type of direct engagement, along with out-of-the-box thinking to reduce complexity and schedule, is another ingredient that makes APL's fabrication operation successful.

Figure 11. EIS and MEGANE electromagnetic interference shielding gasket.

ADDITIVELY MANUFACTURED TOOLING FOR EUROPA CLIPPER AND MARTIAN MOONS EXPLORATION INSTRUMENTS

One of the most innovative breakthroughs in prototype manufacturing has been rapid development and integration of unconventional tooling. Traditionally, novel tooling has been fabricated by subtractively machining from metal billets. This process requires significant time and resources and is subject to the constraints of machining methods. The integration of additive manufacturing enables a new rapid and highly adaptable solution to achieving complex fabrication requirements that once were difficult and cost prohibitive. APL took full advantage of this advancement to fabricate custom tooling for instruments on NASA's Europa Clipper, a mission to explore Jupiter's icy moon, Europa, and the Japan Aerospace Exploration Agency's MMX.

Both spacecraft require highly specialized instruments with novel electronics shielding components. Because of the small form factor of the electromagnetic interference shielding (Figure 11), fabrication presented a significant manufacturing challenge. Designers and fabricators discussed the possibility of using rapid prototyping and engineered additively manufactured materials to fabricate forming tools to accommodate the small form factor and tolerance. The scope of work fell into the micro–sheet metal category, which is common in electronics design and components. Mechanical fabricators, mechanical engineers, and electrical fabricators collaborated to determine that the complex shielding shape for Europa Clipper's Europa Imaging System (EIS) and MMX's Mars-moon Exploration with GAmma rays and NEutrons (MEGANE) could be manufactured quickly in low volume by using polymer additive tooling. Technical experts in the mechanical fabrication area designed and fabricated polymer form tools in fewer than 48 h to produce multiple versions of the 100-µm-thick beryllium copper components. Leveraging expert knowledge in additive manufacturing processes, materials, and finite element analysis, the team generated a design that was structurally compliant and dimensionally accurate.

The tooling was fabricated so that it could accept interchangeable inserts to accommodate different versions of the connectors for pin count, flange length, and bend radii. One of the unique challenges was the 0.006-in. bend radius; no existing standard tooling offered this radius. One of APL's sheet metal technicians proposed using a standard utility knife blade whose edge was rounded to a 0.005-in. radius—a solution that was safe for the fabricator and would not damage the part. Working closely with the inspection team, the fabricator used metrology tools to measure the radius of the blade after burnishing until it met dimensional requirements. This blade geometry was debossed into the tool holder design to capture it securely (Figure 12). Steel dowel pins replaced the back gauge for length control because the gauge on the press brake machinery could not accommodate such thin and small parts (Figure 12).

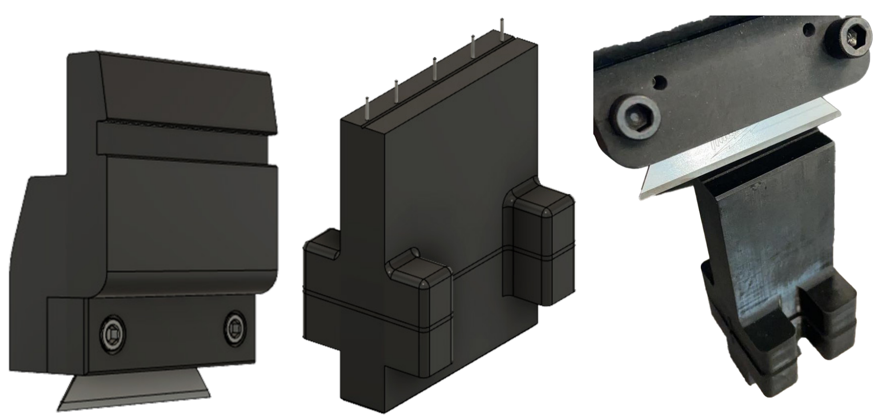

Figure 12. Custom tooling for the EIS and MEGANE. Left, model of the beryllium copper punch tool with the utility blade. Middle, model of the beryllium copper bending die with dowel gauges. Right, the completed tool.

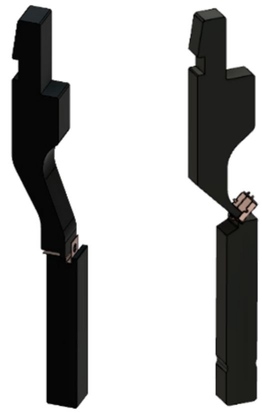

Figure 13. EIS and MEGANE printed wiring board components. Left, the EIS polymer forming tool verification model. Right, the EIS surface-mount printed wiring board shield with integrated solder pins (enabling clearance and bending verification).

Several other printed wiring board components were fabricated using additive tooling when feature dimensions and sizes did not allow for the use of conventional tools. CAD models of the tools allowed the bend clearance to be verified (Figure 13). Additionally, these fabrication efforts were ultimately part of a feasibility study that engineers could use in future manufacturing and design.

Multiple discoveries resulted from this manufacturing solution. Collaboration across multiple disciplines allowed for new capabilities to be integrated into the manufacturing process successfully and rapidly. Use of new technologies and novel approaches to manufacturing removed constraints to electronics and instrument design. In addition, these efforts unlocked applications for functional end-use additively manufactured components. The increasing use of additive manufacturing is due in part to the feasibility results from the fabrication of the electronics shielding components.

SUMMARY

APL's ability to leverage modern manufacturing processes—along with its collaborative approach in which knowledgeable manufacturing personnel directly interact with engineers, designers, and research scientists—has contributed to the success of many critical programs. This article highlights just a sample of the creativity and collaboration required to fabricate components for complex systems. The expanded role fabricators now often play in the design and development of these systems has required them to continue to expand their technical knowledge. In addition to mechanical aptitude, APL fabricators have the ability to use and understand design and manufacturing software. This knowledge and ability enables them to collaborate with designers and engineers at all stages of the design and fabrication process, as well as to program APL's cutting-edge equipment to solve complex challenges.

ACKNOWLEDGMENTS: We thank Steven Storck for his contributions to this article. Thanks to David Everett, Bryan Martin, and Michael Viens and the NASA Goddard Space Flight Center Optical Bonding Working Group for their assistance with the DRACO mirror hanger redesign.

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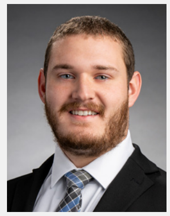

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