# Manufacturing & Prototyping

## High-Pressure Lightweight Thrusters

### Carbon/carbon composite structures are braided over iridium-lined mandrels and densified by chemical vapor infiltration.

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Returning samples of Martian soil and rock to Earth is of great interest to scientists. There were numerous studies to evaluate Mars Sample Return (MSR) mission architectures, technology needs, development plans, and requirements. The largest propulsion risk element of the MSR mission is the Mars Ascent Vehicle (MAV). Along with the baseline solid-propellant vehicle, liquid propellants have been considered. Similar requirements apply to other lander ascent engines and reaction control systems.

The performance of current state-of-the-art liquid propellant engines can be significantly improved by increasing both combustion temperature and pressure. Pump-fed propulsion is suggested for a single-stage bipropellant MAV. Achieving a 90-percent stage propellant fraction is thought to be possible on a 100-kg scale, including sufficient thrust for lifting off Mars.

To increase the performance of storable bipropellant rocket engines, a high-pressure, lightweight combustion chamber was designed. Iridium liner electrodeposition was investigated on complex-shaped thrust chamber mandrels. Dense, uniform iridium liners were produced on chamber and cylindrical mandrels. Carbon/carbon composite (C/C) structures were braided over iridium-lined mandrels and densified by chemical vapor infiltration. Niobium deposition was evaluated for forming a metallic attachment flange on the carbon/carbon structure. The new thrust chamber was designed to exceed state-of-the-art performance, and was manufactured with an 83-percent weight savings.

High-performance C/Cs possess a unique set of properties that make them desirable materials for high-temperature structures used in rocket propulsion components, hypersonic vehicles, and aircraft brakes. In particular, more attention is focused on 3D braided C/Cs due to their mesh-work structure. Research on the properties of C/Cs has shown that the strength of composites is strongly affected by the fiber-matrix interfacial bonding, and that weakening interface realizes pseudo-plastic behavior with significant increase in the tensile strength. The investigation of high-temperature strength of C/Cs under high-rate heating (critical for thrust chambers) shows that tensile and compression strength increases from 70 MPa at room temperature to 110 MPa at 1,773 K, and up to 125 MPa at 2,473 K.

Despite these unique properties, the use of C/Cs is limited by its high oxidation rate at elevated temperatures. Lining carbon/carbon chambers with a thin layer of iridium or iridium and rhenium is an innovative way to use proven refractory metals and provide the oxidation barrier necessary to enable the use of carbon/carbon composites. Due to the lower density of C/Cs as compared to SiC/SiC composites, an iridium liner can be added to the C/C structure and still be below the overall thruster weight. Weight calculations show that C/C, C/C with 50 microns of Ir, and C/C with 100 microns of Ir are of less weight than alternative materials for the same construction.

*This work was done by Richard Holmes of Marshall Space Flight Center and Timothy McKechnie, Anatoliy Shchetkovskiy, and Alexander Smirnov of Plasma Processes, Inc. For more information, contact Sammy Nabors, MSFC Commercialization Assistance Lead, at sammy.a.nabors@nasa.gov. Refer to MFS-32883-1.*

## Non-Magnetic, Tough, Corrosion- and Wear-Resistant Knives From Bulk Metallic Glasses and Composites

### High-performance knives are used in hunting, fishing, sailing, diving, industrial, and military applications.

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Quality knives are typically fabricated from high-strength steel alloys. Depending on the application, there are different requirements for mechanical and physical properties that cause problems for steel alloys. For example, diver's knives are generally used in salt water, which causes rust in steel knives. Titanium diver's knives are a popular alternative due to their salt water corrosion resistance, but are too soft to maintain a sharp cutting edge. Steel knives are also magnetic, which is undesirable for military applications where the knives are used as a tactical tool for diffusing magnetic mines. Steel is also significantly denser than titanium (8 g/cm$^3$ vs. 4.5 g/cm$^3$), which results in heavier knives for the same size. Steel is hard and wear-resistant, compared with titanium, and can keep a sharp edge during service. A major drawback of both steel and titanium knives is that they must be ground or machined into the final knife shape from a billet. Since most knives have a mirrored surface and a complex shape, manufacturing them is complex. It would be more desirable if the knife could be cast into a net or near-net shape in a single step.

The solution to the deficiencies of titanium, steel, and ceramic knives is to fabricate them using bulk metallic glasses (or composites). These alloys can be cast


A full tang **Bulk Metallic Glass Tactical Knife** with multi-faceted blade surface and carbon fiber grip with titanium pins, fabricated by Benjamin Potter of Altadena, CA. The knife was fabricated by water-grinding from a larger plate as an illustration. In a commercial setup, the knife would be cast to a net-shape using an auto-feed and eject system, similar to what is done in plastics.

into net or near-net shaped knives with a combination of properties that exceed both titanium and steel. A commercially viable BMG (bulk metallic glass) or composite knife is one that exhibits one or all of the following properties: It is based on titanium, has a self-sharpening edge, can retain an edge during service, is hard, is non-magnetic, is corrosion-resistant against a variety of corrosive environments, is tough (to allow for prying), can be cast into a net-shape with a mirror finish and a complex shape, has excellent wear resistance, and is low-density. These properties can be achieved in BMG and composites through alloy chemistry and processing. For each desired property for knife fabrication and performance, there is an alloy development strategy that optimizes behavior. Although BMG knives have been demonstrated as far back as 1995, they never found commercial success because they had to be ground (which presented problems because the alloys contained beryllium), they weren't low cost (because they weren't cast to a net-shape), they were brittle (because they were made with a low-quality commercial material), and they had extremely poor corrosion resistance (because corrosion was not well-understood in these materials). Ultimately, these shortcomings prevented the widespread commercialization.

In the current work, the inventors have applied more than a decade of research on BMGs from Caltech and JPL to develop a better understanding of how to make BMG knives that exhibit an optimal combination of properties, processing and cost. Alloys have been developed based in titanium (and other metals), that exhibit high toughness, high hardness, excellent corrosion resistance, no ferromagnetism, edge-retaining self-sharpening, and the ability to be cast like a plastic using commercially available casting techniques (currently used by commercial companies such as Liquidmetal Technologies and Visser Precision Casting). The inventors argue that depending on the application (diving, military, tactical, utility, etc.) there is an optimal combination of design and alloy composition. Moreover, with new casting technologies not available at the inception of these materials, net-shaped knives can be cast into complex shapes that require no aftermarket forming, except for sharpening using water-cooled polishing wheel. These combinations of discoveries seek to make low-cost BMG knives commercially viable products that have no equal among metal or ceramic knives. Current work at JPL focuses on net-shape casting of these alloys and testing their mechanical properties versus commercially available knives to demonstrate their benefits.

*This work was done by Douglas C. Hofmann of Caltech and Benjamin Potter for NASA's Jet Propulsion Laboratory. For more information, contact the inventors at dch@jpl.nasa.gov. NPO-48850*