FibriloidCR™: Bearings for the New Space Mission

Introduction

Next to springs and fasteners, bearings are one of the most over-looked and under-appreciated mechanical components in our industrialized society. Wheels would not turn, joints would not articulate, and spinning shafts would grind to a halt in a bearingless world. We are a world of moving parts, yet today, bearings are still a niche market with a small number of experienced competitors battling fiercely in this highly specialized industry. Of this elite number, RBC is one of the world's largest bearing manufacturers with offices, distributorships, and research facilities that span the globe. Bearings are generally placed in two categories: rolling element (i.e. ball bearings contained in race) and plain (i.e. self-aligning ball joints or sleeves). **Figure 1** shows examples of the different types of bearings. **Figure 2** displays a brief snapshot of RBC's worldwide footprint.

Figure 1. A selection of the wide assortment of bearing-related products

Of the 30 RBC divisions worldwide, Transport Dynamics of Santa Ana, California will be the focus of this article. It was here, over 50 years ago, that the world's first self-lubricating bearing material was invented [Patent No. USRE24765]. This revolutionary composite design allowed for superior vibration damping, extending the fatigue life of vibrating structures. It also offered a vast improvement in load to weight ratio over rolling element bearings, increasing load-carrying capacity while simultaneously decreasing in overall size. Finally, the self-lubricated solution eliminated the need for grease in many applications, improving maintenance costs and mechanical longevity.

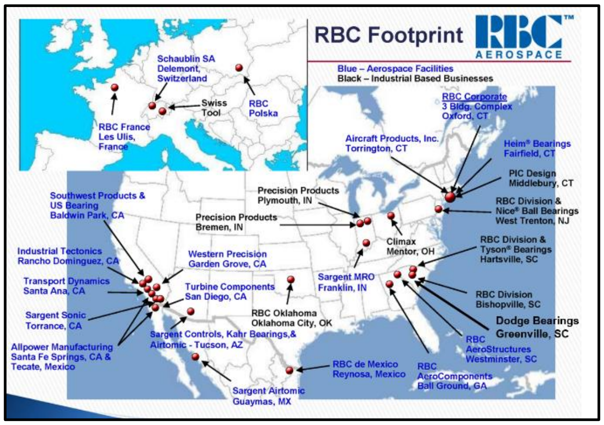


Figure 2. RBC Bearings' global presence

These improvements were not limited to aerospace for long, and were soon adapted into most mechanical designs from tanks to bulldozers to food packaging. Since this material's inception, it has proliferated into the ground power, civil engineering, and maritime industries, to include a few.

Although simple in concept, the plain bearing (and the materials within) are highly engineered. Each design and material combination is tailored to the specific needs of the customer and application. **Figure 3** illustrates a standard spherical (self-aligning) bearing; these artificial joints can be as small as an insect or large enough to support the weight of a bridge.

Figure 3. Several varieties of spherical bearing

In the past, spherical bearing research and development has centered around optimizing shape and composite material combinations to improve load carrying characteristics, decrease coefficient of friction, and increase high temperature stability. Transport Dynamics has its own state-of-the-art laboratory dedicated to developing these new designs and testing them under the most rigorous conditions.

Developed by an elite consortium of engineers from SAE and the United States Navy, the standards that govern bearing performance and manufacture were drafted to qualify only the most robust designs. These standards (i.e. AS81820, AS81934, and AS81935) are used as the paradigm for testing, even in industries that do not have passenger safety concerns like missiles, drones, and satellites.

The “New” Space Mission

In the 30 years after Sputnik, space travel was confined to low earth orbit with the occasional lunar excursion; the mission was driven mainly by nationalistic competition with the secondary goal of research. Since the late 1990’s, advancements in communication technology and the advent of GPS expanded the desire for companies and governments to invest in satellite technologies that operate in higher orbit; the strategic value of high earth orbital dominance is clear from both a financial and military sense. This race continues today, with companies like Virgin Orbit, Relativity Space, Blue Origin, SpaceX, and ULA joining the push to develop cost effective, reusable launch systems to flood the sky with satellites. However, the real developments have come in the last decade with many companies committing vast resources in support of LEO satellite constellations, off-world manufacturing, asteroid/planetoid mining and interplanetary colonization.

However, building vessels large enough to ferry entire colonies of people and material across the interplanetary gulf must be done in low (or zero) gravity, like the moon. In order to move enough bulk material and manpower off-world to create bases suitable for ship construction, a massive amount of infrastructure must be developed and commercially crewed space missions must become safe, reliable, and financially viable. This is where the reusability model has taken off; instead of building rocket & satellite components to be disposable, space manufacturers are seeing the virtues of investing in tailored engineering solutions utilizing high-performance materials and rigorous testing dedicated to the extremes of space travel.

The Difficulties with Bearings in Space

On earth, standard operating temperatures for a self-lubricated bearing generally range from -65°F (outside air temperature during flight) to 650°F (third stage of a turbine engine). In this environmental range, moisture, salinity, and contamination are mostly a concern for the bonding substrate. With the exception of highly corrosive environments, the composites used in bearings are stable. Common substrate materials include high-strength, low-alloy steels (4000 series), high carbon martensitic stainless steels (400 series), aerospace grade aluminum (2000, 5000, and 7000 series), titanium, and martensitic precipitation-hardening steels (13-8 ph, 17-4 ph, and 15-5 ph). **Figure 4** displays a few common aerospace metals.

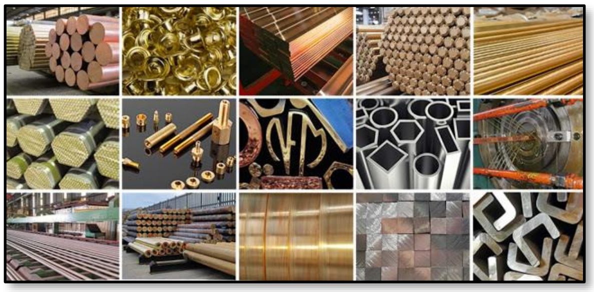


Figure 4. Some common aerospace metals

Unlike standard terrestrial applications, the materials used in space-faring applications have a different set of requirements; this is especially true of bearings. Similar to aerospace, structural materials used in space applications must be lightweight, stiff, and resist fatigue failure during high-cycle vibration. However, the temperature ranges are quite different. Materials used in reusable launch vehicles must endure the massive thermal gradient occurring from sea-level (75°F) to hard vacuum (-454°F) and back through the heat of re-entry.

The drawback with many conventional structural (bearing) materials in space is that they undergo a volumetric phase transformation from a ductile, shock absorbent crystalline structure to one that is hard, brittle, and incapable of sustaining bending moments or impact. This is known as the ductile to brittle transition and happens to mild steel around -100°F (**Figure 5**). Additionally, most launch and recovery sites are located adjacent to, or in the ocean; high-strength, hardened steels are particularly susceptible to stress corrosion cracking in marine atmospheres.

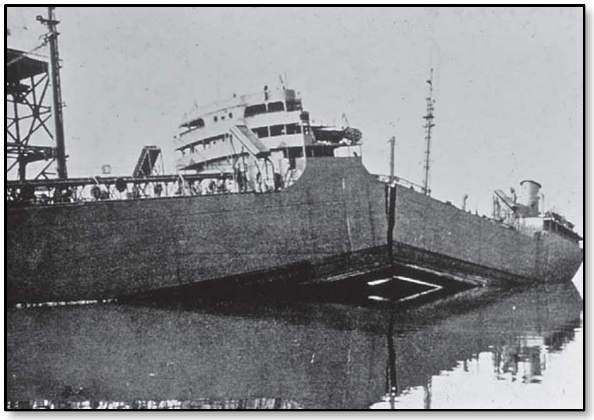


Figure 5. Catastrophic example of ductile to brittle transition in steel

The next challenge for bearings in space is the functionality of the self-lubricating composite. Like many steels, polymer matrix composites (PMC's) also have a finite temperature performance band; below the glass transition temperature, molecular mobility drops by several orders of magnitude leading to significant decreases in damping, toughness, ductility, and drawability. While all of those qualities are important in a bearing material, loss of drawability is possibly the greatest drawback; self-lubricating bearings require film-forming elements to be sacrificially pulled from the composite and drawn, via shear stress, into a transfer film (**Figure 6**).

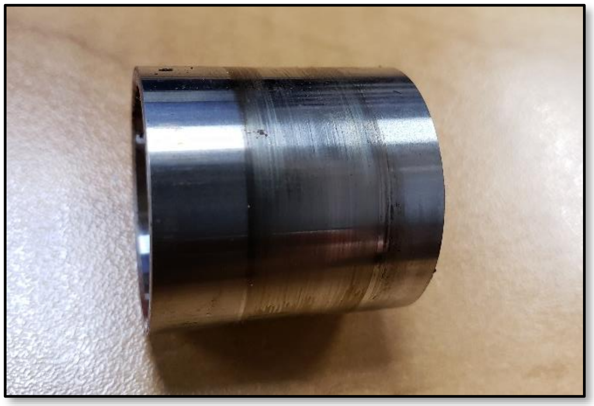


Figure 6. PTFE transfer film burnished onto a counterface bushing

A transfer film protects both composite and counterface by creating a boundary layer where lubricious material is not lost, but instead moves back and forth across the load zone, preserving both surfaces. However, in the cryogenic environment of space, it is difficult to form an adequate transfer film and the bearing continues to wear abrasively throughout its service life. This requires the material to be preferentially abrasion resistant as well as lubricious.

Another issue for bearings in space is the chemical environment. While still relying on solid fuel for the booster phase, many modern rockets use so-called "liquid engines" for their main thrust. These engines work by combining the highly-explosive fuel source (liquid Hydrogen, a.k.a. LH_2) with a powerful oxidizer (liquid Oxygen, a.k.a. LOx). When the two pressurized liquids are combined and ignited, the reaction (see **Equation 1**) creates steam and a massive amount of energy. This fuel source is not only completely "green", but also generates the greatest thrust per pound making it the most efficient rocket fuel in service. Unfortunately, while not flammable itself, LOx, a powerful oxidizer, can combine with many types of materials to create fire and explosion hazards. If the LOx pressure is great enough, even metals can burn in its presence. Hydrocarbon materials (including PMC's) submerged in LOx have the potential of exploding if the system receives sufficient impact. This explosion can then set off a chain reaction with devastating consequences. Therefore, extra consideration must be taken when selecting materials.

Equation 1. Liquid engine combustion equation

$$2H_2 + O_2 = 2H_2O + ENERGY$$

The final hurdle for space bearings is the dramatically expedited production timelines of competitive rocket & satellite manufacturers. With zero sacrifice in quality, the expected lead time for the space industry is roughly a third of the standard lead time for high-precision aerospace bearings & rod ends. This demand for rapid turnaround forced a reevaluation of standard aerospace manufacturing protocol and resulted in streamlining the design & fabrication process.

Testing for Space

Typical plain bearing and rod end qualification testing is performed every two years and overseen by NAVAIR (Naval Air Systems Command) and ACBG (Airframe Control Bearings Group). This testing defines strict performance criteria with regard to oscillatory wear at multiple temperatures, torque, adhesive performance, fatigue, and static loading. **Table 1** describes a typical AS81820 & AS81935 retention of qualification test matrix.

However, despite the rigor of this testing, the space mission requires yet another layer of examination. **Table 2** outlines a typical test matrix for bearings and rod ends dedicated to space applications. As illustrated by this table, space requirements include most of the standard qualifications, the difference being a reduction in contamination concerns and an increased focus on tribology, fatigue, and static loading properties under cryogenic conditions (T ≤ -300°F).

In order to collect data under cryogenic conditions, many special adaptations were required:

Test Frame Upgrades:

- Structural reinforcement to accommodate higher loads and larger bearings
- In-line torque sensors to capture real-time torque/friction data
- LVDT (radial play) sensors actuated remotely by ceramic indices
- Precision-directed, forced air warming circuit to protect steel frames from cryogenic embrittlement
- Custom-built urethane foam and fiberglass/epoxy environmental chambers

Data Collection Upgrades:

- System deflection versus temperature calibration curves established per test frame for enhanced data filtration
- PID-controlled, negative-feedback liquid nitrogen delivery system custom-built

Table 1. Typical aerospace bearing & rod end "Retention of Qualification" test matrix

Specification	Test Type	Sub-Category	Parts
AS81820 D	Radial Static Limit & Ultimate Load	Ambient	3
	Axial Static Limit & Ultimate Load		3
	Oscillation Under Radial Load	Ambient	3
		Contaminant	3
		325°F	3
	No-Load Rotational Breakaway Torque	Ambient	3
	Liner Condition	Bond Integrity	6
		Peel Strength	
	Conformity	n/a	1
AS81935 C	Radial Ultimate Static Load	Ambient	3
	Axial Static Proof Load	Ambient	3
	Fatigue Load	Ambient	3

Table 2. Test matrix for space applications

Specification	Test Type	Sub-Category	Parts
Patterned after AS81820 D	Radial Static Limit & Ultimate Load	Cryo	6
		Ambient	6
		325°F	6
	Axial Static Limit Load	Cryo	6
		Ambient	6
	Oscillation Under Radial Load	Cryo	6
		Ambient	6
		325°F	6
	No-Load Rotational Breakaway Torque	Cryo	6
		Ambient	6
	Liner Condition	Bond Integrity	12
		Peel Strength	
	Loaded Rotational Breakaway Torque	Cryo	12
	Conformity	n/a	2
Patterned after AS81935 C	Radial Static Limit & Ultimate Load	Cryo	6
		Ambient	6
	Axial Static Proof Load	Ambient	6
	Fatigue Load	Cryo	6
		Ambient	6
	Loaded Rotational Breakaway Torque	Cryo	6

- Sensors, LN2 delivery system, and control system integrated into single LabVIEW administrator program

Test Tooling

- Over 80 pieces of custom tooling fabricated from super alloys, high-strength steels, aerospace-grade aluminum, and engineering ceramics

Conclusion

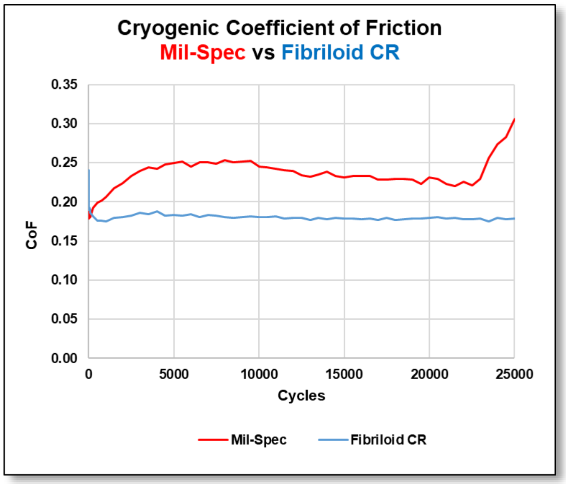
In general, standard testing takes between 12 – 16 weeks depending on the quantity of bearings requiring recertification. However, comprehensive testing for space applications spanned an entire year.

The final product, known as FibriloidCR™, combines cutting edge nano-composites technology, superalloys, and some specialized processing into the first high-performance bearing dedicated solely to the space industry. When tested against the Mil-Spec standard bearing under high loads and cryogenic temperatures, the test results confirmed that conventional bearing materials do not suffice in this demanding new environment. **Figure 7** illustrates the performance differences between these two systems under the most rigorous conditions: 40 ksi of bearing stress and -300°F.

In **Figure 7 (Top)**, the Mil-Spec bearing demonstrates an inconsistent coefficient of friction caused by abrasive wear continually altering the surface finish of the mating couple. This is further evidenced by shape of the wear curve in **Figure 7 (Bottom).** In this graph, the Mil-Spec bearing remains in the abrasive wear regime (positive slope), never entering the optimal adhesive wear regime and achieving a steady state (horizontal slope). However, under the same test conditions, FibriloidCR™ exhibited a uniform coefficient of friction and achieved adhesive wear (steady-state) in about 15,000 cycles.

A post-test examination of the Mil-Spec samples showed both accelerated wear of the composite liner and severe damage to the counterface; as the counterface becomes damaged by abrasive wear, the resultant increase in surface finish synergistically increases the wear rate on the composite. This results in reduced bearing life and increased coefficient of friction (recorded as torque). In contrast, the FibriloidCR™ bearing (composite) retained more than 25% of its usable life and the metallic counterface remained pristine.

FibriloidCR™ bearings and rod ends meet AS81820 & AS81935 requirements, operate with high tribological performance under cryogenic conditions, and excel at both high load + low-frequency vibration & low load + high-frequency vibration. *See the following catalogue pages for ordering details.*



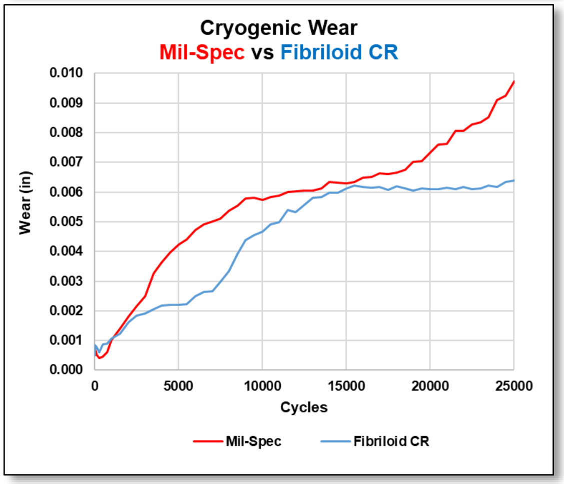


Figure 7. Test data from cryogenic oscillation under radial load, 40 ksi bearing stress, 20 cycles per minute, ± 25° angle of oscillation (Top) Coefficient of friction data; (Bottom) Wear data