CASE STUDY:
Pedaling Faster with Praxis

TITANIUM MIM FOR BICYCLE FREEHUB BODIES

PRAXIS TECHNOLOGY
Advancing Titanium

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The drive to reduce the weight and increase the speed of high-performance bicycles is an uphill climb. Every unnecessary ounce of material needs to be removed to reduce strain on the cyclist and help them maintain a competitive edge. Designers are also concerned with reducing drag, as any effort used to overcome drag is not used to propel the bicycle forward. Additionally, the materials used must be strong and fatigue resistant to prolong the life of the parts.

While sleek frames and thin rims may come to mind, there are other essential components that make a bicycle more competitive. One such component is the freehub body, which is how energy is transferred from the bicycle pedals and chain to the rear wheel.

Titanium is an excellent alternative to aluminum and steel for freehub bodies, and when the part is formed through metal injection molding (MIM), the result is a high-performance, light-weight, durable freehub. Titanium MIM (TiMIM) offers a promising alternative to more traditional materials and manufacturing methods, such as casting, machining, or additive manufacturing.

26 55.845 **Fe** Iron (steel)	**Strong and Inexpensive**	➡	**Dense and Heavy**
13 26.982 **Al** Aluminum	**Lightweight**	➡	**Suffers from Wear and Fatigue Failires**
22 47.867 **Ti** Titanium	**More Expensive**	➡	**Higher Strength-to-weight Ratio, Hardness, and Fatigue Limit**

The Challenge

Boyd Cycling, a high-quality, family-owned craft wheel manufacturer, was designing a new line of lightweight road hubsets. As a company that strives for both quality and affordability, they were looking for the best material and manufacturing method for a new freehub body. Their considerations included:

Performance **Weight** **Marketability** **Cost**

What is a Freehub Body?

The freehub body contains the structural parts that make up the rear axle. It holds the sprockets (cassette cogs) used for changing gear ratios, the spacers, several sets of bearings, and the drive and coaster mechanisms. The drive performs the energy transfer between the chain and rear wheel, and the coaster allows the bicycle to continue rolling without pushing the pedals.

A freehub body is a complex and vital part, and the result of many years of improved bicycle design. But the part is often heavy and the source of drag and lost energy, especially as it begins to wear.

Standard Freehub Technology

Freehubs today are typically made from one of several alloys. Steel alloys are used in inexpensive bicycles due to their low cost and high strength. Aluminum alloys are used in high-end bikes because their low density significantly drops the weight of the part.

There are some limitations with each of these technologies, however.

Steel alloys are heavy and subject to oxidation (rust). The weight of a steel freehub body can be as much as a pound. Furthermore, rust can damage the hub and add to the drag, or get inside the freehub body and damage the bearings. Because the hub is constantly exposed to the environment, moisture can get inside the body quickly, reducing the life of the part.

Aluminum alloys are lightweight and are not as likely to be affected by corrosion. Aluminum alloys produce a thin oxide layer that actually protects the surface rather than destroys it. The main drawbacks of aluminum are its lack of strength and hardness (particularly that the cassette cogs can scar it) and fatigue limit.

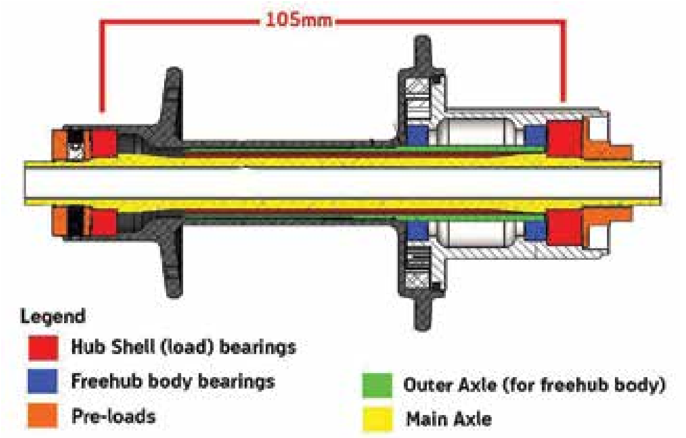
PRAXIS TECHNOLOGY'S INNOVATIVE SOLUTION:

Titanium MIM Freehubs

Praxis' solution for Boyd Cycling was to improve freehub performance and durability by manufacturing them out of titanium using our proprietary TiMIM process. By using titanium, we took advantage of the metal's superior strength-to-weight ratio, fatigue limit, hardness, and corrosion resistance.

We created a part that included all of the internal and external features they required.

One challenge we had to solve during product development involved sintering. Sintering on only the bottom created drag, which caused distortion, but sintering on the flange also distorted due to slumping. The solution Praxis developed used specially designed setters to support both the bottom and the flange at the critical point in the sintering cycle.



EXTERNAL FEATURES:

- Minimal draft on spline features
- Large flange with thin to thick section
- Thickness variations

INTERNAL FEATURES:

- Undercut gusseted section with soluble core

Soluble Core & Flow Simulation

Furthermore, the internal complexity and lightweighting goals required a soluble core that was removed after molding. A core is an internal structure that provides a surface to mold against during injection molding, but then is removed after injection. Usually, this action is built into the tooling. The cores used for this project were soluble, meaning they were dissolved out of the freehub while it was in the green state. Soluble cores were employed because conventional approaches could not form the complex internal geometries..

Before the TiMIM molds could be constructed, flow of the material into the mold was evaluated using mold flow simulation software. The molten feedstock had to not only reach all of the tiny spaces of the mold, but also had to maintain a high enough temperature that the material could still flow freely. Otherwise, a condition known as a "cold flow" could have occurred, preventing the melt fronts from properly consolidating. This adequate fill rate and balanced flow were achieved by adjusting the location of the gate based on the results of the simulation.

To achieve the high injection rate, mechanical modeling was also conducted to ensure that the material did not damage the soluble core. Because of the high injection rate, air in the mold had to evacuate quickly through vents. If air got trapped in the mold, it could have led to surface defects or pores. Vent placement was part of the modeling and simulation that went into the design of these molds.

ADVANTAGES OF MAKING FREEHUBS WITH

Titanium

Titanium alloys, such as Ti-6Al-4V, are commonly used in applications that require high corrosion resistance and a high strength-to-weight ratio. Titanium alloys have the advantages of a higher fatigue limit and better hardness than aluminum. While titanium alloys can be expensive, using TiMIM greatly reduces material waste, making titanium freehubs an economical choice for high-end freehubs.

26 55.845 **Fe** Iron (steel)	13 26.982 **Al** Aluminum	22 47.867 **Ti** Titanium
✔ Strong / Hard ✖ Heavy	✔ Light ✖ Soft / Indents	✔ High Strength-to-weight Ratio ✔ Corrosion Resistant ✖ Expensive

Strength-to-Weight Ratio

One of the most important features of any structural alloy is its strength-to-weight ratio. For buildings, steel is the champion because it is inexpensive, and the weight does not matter. For mobile applications, however, the strength-to-weight ratio must be considered, because energy is required to move the metal parts.

Strength-to-weight ratio is more appropriately called "strength-to-density ratio," as it is the yield strength of the material divided by its density. The yield strength is the stress required to deform a material permanently; to transition it from elastic (temporary) deformation into plastic (permanent) deformation.

Material	**Yield Strength** (MPa)	**Density** (g/cm3)	**S to W** (Yield Strength/ Density) (MPa *cm3/g)
4340 Steel	470	7.78	60.0
17-4 PH Stainless Steel	1105	7.75	143
6061-T6 Aluminum Alloy	276	2.70	102
Ti-6Al-4V Titanium Alloy	**880**	**4.43**	**198**
AZ63 Magnesium Alloy	97	1.83	53.0

Table 1: Strength-to-Weight Ratios for Commonly-Used Alloys [1]

Fatigue Limit

When a part is stressed cyclically, it can fail due to fatigue. Fatigue is characterized by the number of loadings it takes for a part to fail, where the higher the load, the fewer loadings it can withstand. Because the number of loadings is often very high, fatigue tests are displayed on a logarithmic scale.

Damaged Aluminum Freehub Body

At first glance, fatigue testing numbers seem impossibly high; perhaps an alloy fails at a particular load on the order of 109 cycles under controlled conditions, while other factors, such as corrosion or high impact, can reduce this number of loadings. Consider a bicycle wheel that develops a 20 Hz vibration due to an imbalance or out-of-roundness. Even though the stress is low, the number of cycles adds up quickly; every hour the wheel is in operation, it experiences thousands of cycles.

Steel and titanium alloys have fatigue limits, below which any load will not cause the material to fail. Other materials that don't have fatigue limits, such as aluminum, will eventually fail no matter how low the load. With steel and titanium alloys, the metal would not fail by fatigue even under trillions of cycles, as long as the design keeps the stress below the fatigue limit. This gives titanium alloys an advantage over aluminum alloys for high-end freehub bodies, as they will not fail due to fatigue.

Corrosion Resistance

Aluminum alloys produce a protective, thin oxide layer that protects the part against corrosion, but steel alloys are prone to rust (oxidation). Although stainless steel is resistant to corrosion, it can eventually rust if exposed to harsh conditions for extended periods of time. Rust damages the freehub and bearings, increases drag, and reduces the life of the part.

Titanium alloys are used in medical devices due in part to their resistance to corrosion. The human body is a challenging environment, where saline and acidic solutions constantly attack materials. While corrosion resistance is not as mission-critical in bicycle freehub bodies as it is in medical implants, high corrosion resistance makes the freehub body more robust.

With most bicycle races occurring outdoors, bicycles are constantly sprayed with water and mud. The freehub body is subject to a chemical attack on every race. The cyclist may wipe down the bike after a race, but any hard-to-reach areas will be subject to corrosion between races as well. With titanium alloys, corrosion is significantly reduced, which means parts will last longer and will run smoothly for many years.

Wear Resistance

While freehub bodies are designed to reduce unnecessary friction, some is required to drive the rear wheels and allow the bicycle to coast. All of the friction in these parts, whether necessary for drive or unavoidable, wears on the components. As these components wear, they produce fine wear particles in the form of dust or shavings. These particles increase friction between the moving parts, creating more friction and generating more wear particles.

In some cases, the friction can generate enough heat to form microwelds and galling, where metal particles are smashed and welded into one of the other pieces. With its low melting temperature, aluminum is particularly vulnerable to this type of wear. Although titanium is also prone to galling, its hardness and higher strength make its wear resistance stronger compared to aluminum.

While there is not a widely accepted standard for wear, one measure relates the surface hardness and the Young's Modulus to resistance to wear. There are several formulas and mathematical models that give relative wear resistance figures. [2] While these models are still up for debate, and a discussion of the calculation of the reduced elastic modulus is beyond the scope of this case study, the end result is that the hardness of the material typically increases its abrasion resistance.

On a more basic level, wear resistance comes down to the simple fact that a harder rock will scratch a softer one. Much of the sand and fine dirt that work into bicycle components are hard ceramic. The wear particles are often work-hardened in a well-sealed system, because they are stripped away from the bulk material. This means the wear particles are harder than the surface and can contribute to further wearing.

Because high hardness is desirable, a table of common metals and their Brinnell hardness is shown below:

Material	Hardness (Brinell)
4340 Steel	217
17-4 PH Stainless Steel	352
6061-T6 Aluminum Alloy	95
Ti-6Al-4V Titanium Alloy	**334**
AZ63 Magnesium Alloy	50

Table 2: Brinell Hardness for Common Alloys. [1]

Advantages
OF USING TiMIM

Titanium Metal Injection Molding (TiMIM) is the ideal way to produce freehub bodies. TiMIM is a process where titanium metal powder is mixed with a binder and injected into a mold. The part is removed from the mold and sintered, burning out the binder and bonding the metal particles to form a completed part.

TiMIM parts can be made to very tight tolerances (±0.3%, and as fine as ±0.1% in some cases), are pore-free and hermetic, and have a smooth surface finish. They produce very little waste, and post-processing can be performed on them, depending on the application requirements.

The tight tolerances and smooth surface finish are particularly advantageous in producing freehub bodies, as this limits friction and wear. The TiMIM parts are quickly machined on the inner surface to ensure exact dimensions and perfect fit of the bearing. In this case, the TiMIM operation produces near-net-shape parts, and the inner surface of the freehub body is machined with a few simple operations. This is a drastic improvement in terms of time and complexity as compared to producing parts by CNC machining from bar stock.

The TiMIM process generates very little waste compared to casting operations (which require extensive riser, gate, and sprue networks) and machining operations (which turn much of the stock material into chips). It also produces a finer surface finish than additive manufacturing techniques, without adding extra ribbing and support structures that are often required during the 3D printing process, and which must be removed after printing.

Titanium Metal Injection Molding (TiMIM) is the ideal way to produce freehub bodies...

THE Results

Praxis' client, Boyd Cycling, developed a line of lightweight road hubsets with a titanium body made with TiMIM. The new line was more economical than those with freehubs manufactured by traditional methods. **The manufacturing process generated less waste, with the parts over 99% complete out of the mold, resulting in a significant reduction in cost versus machined freehubs.**

Boyd Cycling's new freehubs were more durable and performed better than traditional freehubs, and the final product passed all lab and road tests. The titanium freehub incurred:

BOYD CYCLING

minimal indentations as compared to an aluminum part and **weighed about 34% less** than a steel part. Testing also showed an about **50% reduction in the rear hub's bearing friction.**

FINAL Thoughts

In the competitive bicycle racing community, every ounce of added weight requires more energy for motion, and every rough edge or worn surface becomes added drag. To maintain a competitive edge, cyclists must shave every unnecessary ounce from their bicycles and reduce drag. Furthermore, all components must be strong and fatigue resistant because the repetitive stresses on components are high in number.

While steel has strength and low cost, it is dense. Aluminum is lightweight but suffers from wear and fatigue failures. Titanium offers some competitive advantages in its high strength-to-weight ratio, relative hardness, and high fatigue limit. While titanium is more expensive, TiMIM reduces material waste and overall cost.

TiMIM, combined with some post-process machining, offered Boyd Cycling an effective alternative for manufacturing freehub bodies. TiMIM's suitability for small complex parts in high production volumes and the fact that it generates little waste made it an ideal candidate when compared to additive manufacturing, casting, and machining techniques alone.

About PRAXIS TECHNOLOGY

Praxis Technology is an FDA-registered, ISO-13485-certified manufacturing company that produces titanium components via powder metallurgy for the medical, aerospace, consumer, and sporting goods markets. We specialize in porous titanium and titanium metal injection molding (TiMIM). Our proprietary process provides high-performance titanium parts for various demanding applications while satisfying stringent regulatory requirements. At Praxis, we recognize the importance of collaboration, from product development to production, and will work with you to create the custom parts you need.

Sources

[1] Matweb.com, accessed 4/18/22.

[2] Pintaude, Giuseppe. Introduction to the Ratio of the Hardness to the Reduced Elastic Modulus for Abrasion. https://pdfs.semanticscholar.org/de64/d02d08a0d23851af1bf5f943dbdb53af26c0.pdf Accessed 4/18/22.

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