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On a roll

David Cooper examines the rolling-element bearing – the different types, materials, applications and how it compares with other bearing technologies

Bearings are possibly one of the more innocuous components of a racing powertrain, but without effective and reliable bearings, any motorsport powertrain would rapidly grind to a disastrous halt. This article is about current trends in powertrain bearing technology; in particular there have been a lot of recent developments in rolling-element bearings, as we identify here.

Bearings can be divided into two broad types – rolling element or contact, and journal or fluid film. As its name suggests, a rolling-contact bearing is one in which the main load is transferred through elements in rolling contact between an outer and inner surface or 'race', as opposed to a journal or fluid-film bearing, where the load is transferred by the relative sliding of a lubricated shaft and bushing (where the lubricant may be fluid or solid film).

While journal bearings find extensive applications in an engine, the wider powertrain is the domain of the rolling-element bearing. Journal bearings are particularly suited to high-speed, high-temperature applications, where space is at a premium, such as for crankshaft main bearings and con rod big- and small-end bearings, where they are used almost exclusively. Rolling-element bearings find applications in areas where the reduction of friction is of paramount importance, although they tend to be more complex to manufacture. They also need far more space, although needle roller bearings can be more competitive in this regard.

One-piece journal bearings, often used in four-stroke con rod small ends and NASCAR camshafts (Courtesy of Dura-Bond)

While the overall design concept for rolling bearings remains fundamentally unchanged, the subtleties of their materials and design have advanced significantly to provide optimum performance and reliability. Rolling-element bearings can take many forms depending on the application, ranging from bearings capable of supporting high radial loads with minimal friction to tapered or axial contact bearings capable of resisting axial loads, so they are a particularly versatile solution.

The mechanisms of bearing failure are a key issue, as it is these mechanisms (alongside the search for reduced friction) that drive material selection and development, and the overall performance of bearings.

Bearing failure

Rolling-element bearings are traditionally made from hardened steel alloys, providing the minimum surface friction and greatest wear resistance possible, while remaining cost-effective to manufacture to high tolerances. With the move to increasing service life and reducing maintenance costs at all levels – from Formula One's mandatory engine and gearbox lifetimes to life expectancies well in excess of 150,000 miles for domestic automotive vehicles – the design, manufacture and installation of highly reliable long-life bearings is vital.

Bearing failure is generally a materials problem, with failure occurring through several mechanisms or combinations of operating conditions. Assuming that a bearing remains correctly lubricated and sealed against the ingress of debris, the primary mechanism is materials fatigue, generally termed rolling contact fatigue (RCF).

Rolling contact fatigue

The ultimate limit on bearing life is failure by RCF, which induces spalling of the material's surface. To combat RCF in steel bearings, it is important to understand the material's tribology – the mechanisms by which the surface of the bearing wears with friction and lubrication.

RCF is a failure mode by which a surface in rolling contact with another begins to deteriorate after the cyclic loading experienced in operation. This failure is linked directly to the stress field within the material in the region just below its surface, generally referred to as the Hertzian contact stresses. Hertzian stresses are proportional to the normal load, and inversely proportional to the contact area, so they are particularly high for ball bearings where there is a minimal contact area. This stress distribution, having its maximum stress at a point below the material's surface, leads to the formation of subsurface cracks as a result of cyclic loading. Once a crack has been initiated below the surface, a flake or chip eventually works loose, and the bearing's performance begins to degrade from this point.

Measures against RCF

To improve the RCF life of steels, various coatings and surface heat treatments can be applied, either by thermal spraying or vapour deposition to apply a harder-wearing coating. Surface coatings of ceramic or harder metals can improve RCF properties, but applying such coatings can be tricky, as thermal mismatch between the coating material and its substrate can lead to residual stresses for example. Coating parameters must also be precisely controlled to ensure consistent coating thicknesses and quality.

Steels may also be case-hardened, or otherwise surface treated to produce a refined surface microstructure that can better resist the loads required.

RCF can be accelerated by problems outside of the bearing itself, such as excessive loading or off-axis loading created by a distorted shaft or misaligned bearings, which can increase the probability of a surface fatigue failure

Possibly the greatest advance though in reducing failure by RCF has been in the ever-improving quality and cleanliness of the steels used. Contaminants within the material can act as stress raisers or nucleation sites for cracking to occur, but by better quality control of the raw materials the likelihood of an early fatigue failure is reduced.

Fatigue is not a standalone problem though; it is likely to be accompanied or accelerated by additional damage from the presence of debris or other abrasive particles, or excessive heat caused by improper or insufficient lubrication.

Lubrication failure

If there is insufficient lubrication then overheating can occur. This overheating, or a breakdown in the lubrication itself, can have various effects on a bearing, any of which alone or in combination can lead to its failure.

Excess heat, caused either by running the bearing beyond its operating speed or load, or by poor lubrication, can affect the performance of lubricants. Heat can ultimately degrade and melt the grease-type lubricants commonly used in sealed bearings, leading to further overheating and a degrading spiral of cause and effect.

Extreme surface temperatures can then alter the material's microstructure within that critical subsurface region, effectively annealing the hardened steels and reducing their mechanical properties once the bearing cools and the microstructure re-crystallises, so reducing the surface hardness and strength. Even if no microstructural change takes place, the mechanical properties of steels degrade quickly with temperature, moving the materials out of their safe operating window with respect to the loads experienced, increasing the chance for failure and accelerating the effect of material fatigue.

In the event of a lubrication failure or reduction, the heat increase in the bearing can also cause micro-weld adhesion. The materials of the rolling element and the race do not have perfectly flat surfaces – as with any machined component, microscopic peaks and valleys are actually present. The lubricant serves to fill the valleys and form a film between the peaks, distributing the load over a contact area and preventing any real surface-to-surface contact.

If this lubrication film breaks down, the peaks may make contact, creating an exceptionally high pressure. These pressures lead to temperature rises, and momentarily friction-weld the tiny contact areas together, before inertia overcomes the micro-weld and the rolling element breaks away. This generates surface damage and debris, accelerating bearing failure. The primary method to combat micro-weld adhesion is therefore to ensure adequate lubrication, and so maintain the bearings at their operating temperature.

Corrosion and debris

The presence of corrosion or rust on the surface of a raceway or rolling element can form surface pitting, which accelerates fatigue failure. Although bearings are stored and packaged with a film of lubricant to keep oxygen from the surface, partial removal of the film during installation, or the presence of water – perhaps via a minor seal failure on a water pump, or through condensation – can provide the opportunity for corrosion to develop.

While journal bearings typically include a soft metal coating designed to capture hard foreign particles via embedding, rolling-element bearings are not so forgiving. The presence of debris can be highly damaging to the surfaces of the rolling elements or races, leading to vibration, increased wear and premature failure. Debris may enter the bearing, or may be generated within the bearing itself via spalling. As the bearing rotates, the particles may then be indented into the raceway, or may gouge it. This surface deformation then leads to increased localised surface stresses that in turn accelerate a fatigue failure, generating more debris and so on.

Brinelling

Brinelling occurs when an excessive (usually one-off) radial loading forces the rolling element to indent the surface of the race, plastically deforming it. This reduces the effectiveness of the bearing, as it will no longer rotate smoothly. False brinelling, which is similar in appearance to brinelling, can also occur if a bearing experiences severe vibration while remaining relatively stationary. Micro-cracking can occur where the rolling elements contact the race, which then leads to premature spalling; however, such a scenario is unlikely to occur within the ever-turning bearings of a powertrain.

Applications

The biggest factor affecting the lifetime of a bearing is its application. Very similar bearings may be used in a circuit race engine and a drag car engine. However, the expectations differ; for many applications, con rod bearings will be expected to last a season before servicing and replacement. The same bearing, in a very similar engine architecture ▶

but within an 8000 hp nitromethane dragster, will be replaced or at least inspected after a bare 4 s or so of full-power running.

Bearing materials

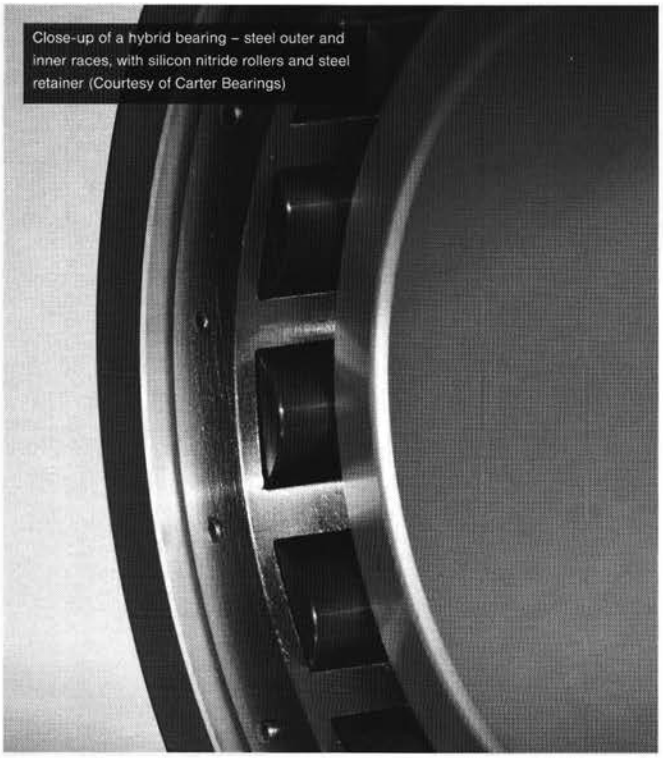
Bearings are normally made from steel alloys, either stainless chromium-based or high-alloy steels for enhanced corrosion resistance or surface hardness. Typically races are made from alloys such as 51200 tool steel, while 440C stainless steel can be used if the application calls for it.

Despite the perceived excellence and growing use of materials such as titanium and high-strength aluminium alloys – and they are undoubtedly excellent in their applications, having fantastic specific (per kg) strength and stiffness – few materials can beat the ultimate properties of steel, particularly given its low cost and high availability, so steel remains the mainstay bearing material. Apart from very high-end or specialist applications, steel has been the only sensible, reliable bearing material choice for rolling bearings throughout the driveline, at least until recently.

Ceramic bearings are the new technology on the block. Although not a recent advance, the use of ceramic materials for bearings has grown significantly, and they are becoming increasingly cost-effective. Bearings can be completely ceramic (rollers and races) but a good combination for performance and cost-effective use appears to be hybrid ceramic bearings.

As they sound, hybrid bearings are a combination of a steel and ceramic bearing, generally a chromium steel race coupled with ceramic ball bearings. The use of high-quality steel and machining processing for the races allows a high surface finish to be achieved, resulting in an exceptionally low-friction bearing.

The rolling elements, having a relatively simple geometry, are presumably more economical to manufacture from ceramic than would be the entire bearing, and the most popular ceramic in use appears to be high-grade silicon nitride, which possesses excellent mechanical properties, with much greater hardness (1500-1600 HV) than can be achieved with steel (up to 650 HV). Silicon nitride rolling elements have a much lower density – 3.2g/cm^3 – making them 60% lighter than steel, which provides benefits not only for static weight but also in reducing inertial loads and parasitic losses.



Close-up of a hybrid bearing – steel outer and inner races, with silicon nitride rollers and steel retainer (Courtesy of Carter Bearings)

Silicon nitride rolling elements begin life as a raw powder material, which is then sintered under extreme temperature and pressure to consolidate a fully dense blank. The blanks can then be machined, typically via a diamond grinding-type process capable of achieving the high dimensional tolerances, along with exceptional surface finish.

Although the performance benefits (low rolling resistance) are available by using a hybrid bearing, the area where hybrids really win out is in reliability and service life. Comments from several bearings manufacturers during the research for this article suggest a general four- to fivefold increase in bearing life for a hybrid bearing over a traditional steel bearing. Depending on the application, this may translate into replacing a bearing after perhaps two or three racing seasons compared to every season with a steel bearing. This increase in service life not only saves the cost of replacing bearings but also the attendant time in replacing or servicing them.

Hybrid bearings can also be more forgiving than steel, as they can survive with less lubrication than an equivalent steel bearing. Ceramic rolling elements have a much lower friction coefficient (about 10% that of steel) so lubrication is not as essential for friction/rolling, while the difference in material – particularly the ceramic's high melting point – removes the potential for failure by micro-weld adhesion. The use of steel races, however, indicates that lubrication will certainly remain a necessity, to prevent contact damage, corrosion and overheating of the steel race.

Retainers

Bearing retainers are required in many forms of rolling-element bearing, as they serve to keep the rolling elements from contacting each other. Depending on the application, retainers can be made from steel or polymers. Retainers need to be stiff enough to maintain the elements' relative positions, although any improvement in weight can only be beneficial.

While machined or pressed steel retainers are common, a trend towards polymers for lower weight and cost is evident, although they are limited by service temperature. PEEK (polyether ether ketone) is an alternative where temperatures and corrosive combustion by-products exceed the abilities of common polymers; the cost trade-off though means steel retainers are likely to remain.

Seals

The modern ball bearing is more often than not a sealed unit, pre-lubricated and sealed at the factory. This guarantees the correct quantity and type of lubrication for the rolling elements while also preventing the ingress of debris – wheel bearings are an

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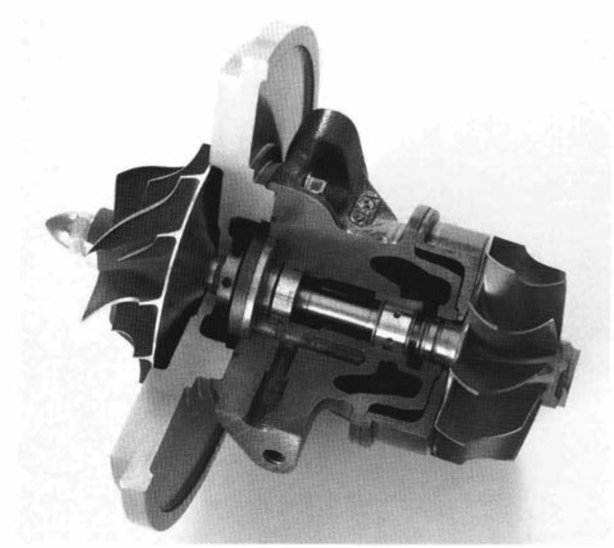
Hybrid turbocharger bearing system, showing thrust bearing and ceramic bearing at left-hand end, journal bearing at right (Courtesy of Turbonetics)



obvious example here. Sealing the bearing also separates it from its environment, allowing the optimum lubricants to be used, for example in the gearbox, and the optimal lubricant for the bearing, rather than requiring the gearbox lubricant to serve two masters.

Seals also protect against the ingress of moisture. While this can cause corrosion of steel raceways, accelerating failure, moisture can also emulsify with the lubricants present, reducing their performance and again leading to failure.

Bearing applications

The applications for steel rolling-element bearings, and now more commonly hybrid bearings, are wide-ranging in the racecar powertrain. Looking deeper into the anatomy of the drivetrain, the bearings are present in a variety of forms. Steel needle rollers, larger roller/barrel bearings and ball bearings all find applications in common types of constant velocity joints; sealed ball-bearing races remain the mainstay for the support of gearbox shafts, while engine ancillaries use many forms of rolling-element bearings to support rotating shafts in water pumps, oil pumps, alternators or belt tensioners.

Although relatively mundane, the consistent and reliable performance of all these bearings remains critical to the smooth running of any racecar. Even if no failure occurs, longer service lives translate to lower maintenance costs. It appears, however, that rolling-element bearings do have a part to play in some of the more exotic future powertrain applications, finding uses in turbochargers and mechanical (flywheel) energy recovery systems – although not without competition from other bearing technologies.

Race Engine Technology

Established in 2003, Race Engine Technology is a unique, high quality review of contemporary racing powertrain technology. It is widely read by design and development engineers and others involved professionally in this worldwide industry and just as avidly by those interested in a subject that has a huge ‘enthusiast’ following. it reaches the majority of all competition engine builders right across the globe - the heart of its readership. It is published by High Power Media which is let by specialist publisher Simon Moss and renowned motorsport editor, Ian Bamsey. HPM also publishes annual technology reports focused on specific forms of motorsports, along with two free-for-life online technical resources, RET-Monitor and F1-Monitor.