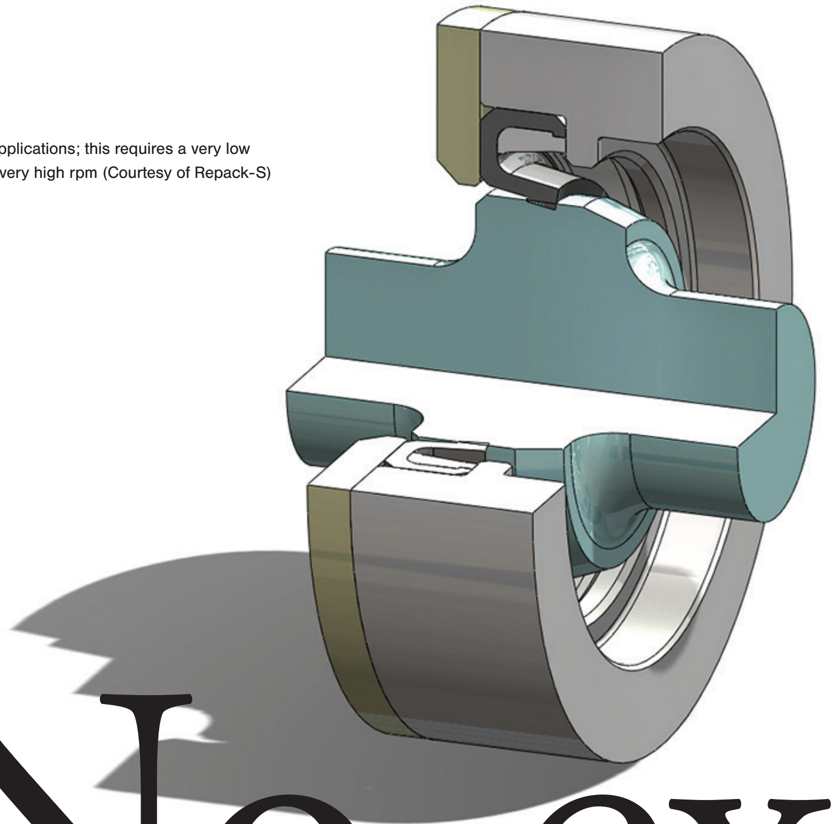
A PTFE lip seal for use in KERS applications; this requires a very low friction seal capable of sealing at very high rpm (Courtesy of Repack-S)



No-exit strategies

Lawrence Butcher looks at some of the latest advances in materials and production methods for dynamic sealing technology

Seals may not be the most glamorous engine components, but without them no modern race engine would be able to operate. As with so many components, a well designed seal is unlikely to win you a race, but a poorly designed one can quickly prevent a car ever seeing the finish.

In a modern race engine, the design requirements for seals continue to grow in complexity. The basic flat gasket is almost consigned to history, its place taken by O-rings and multi-faceted 'form' seals fitted into precisely machined slots. Meanwhile, the design and construction of dynamic seals for applications such as crankshaft sealing has also seen considerable advances.

Design methodology

Speaking to one motorsport seals manufacturer, it was interesting to note the range of different sealing requests it has received. Broadly these can be placed in one of two categories – those intended for use in a clean-sheet design and those for existing engine applications.

Where the application was a clean-sheet design, the earlier the seal manufacturer was involved in the design process the better. This way, the sealing solution specified could best match both the needs of the engine builder, and stay within the bounds of feasibility in terms of engineering a seal.

The most challenging applications still involve the sealing of dynamic surfaces, and in the case of an engine these will be rotating or reciprocating components. From a race engine designer's perspective a seal not only needs to provide the required level of sealing, it needs to fit within a specific area, minimise frictional losses and be as lightweight as possible.

To specify the correct design and material specification, a dedicated seals manufacturer will want as much information as possible on the application. This will include details on the tribology of the parts to be sealed, surface hardness, any coating that may be used, thermal expansion rates and, in the case of rotating shafts, maximum rate of rotation and acceleration. Only once they have this information will they be able to specify the optimum sealing solution. As one manufacturer says, "If you ask me for a PTFE carbon-bronze seal with *x* dimensions, you may as well just say I need four black tyres! To get the best solution, each seal needs be tailored exactly for its application."

All the seals manufacturers spoken to in connection with this article touched on the level of specialist knowledge they have built up, knowledge that is well outside what is needed for more general engineering roles. One supplier cited two particular case studies where an in-depth knowledge of sealing technology brought tangible benefits to both engine performance and reliability. The first involved a crankshaft seal on the front of an existing engine which was presenting persistent sealing problems. On investigation, it turned out that the existing seal was not up to the task required of it and needed revision.

Initially, the request was for a seal to fit within the existing architecture, but on further investigation by the seals supplier it emerged that the ideal solution actually required a larger sealing area. Ultimately, the engine manufacturer was able to increase the area available to mount the seal and a satisfactory solution was found.

This highlights the fact that if the sealing had been taken into consideration at the initial stages of the engine's design, the problems could have been averted. As it was, due to having to revisit that particular area of their engine's design, the engine builder actually found a number of other areas that could be improved beyond simply the crank seal specification.

The second case relates to the parasitic power losses associated with both engine and drivetrain seals. Looking at a complete engine and transmission package, the number of seals on rotating and reciprocating components is quite substantial. The frictional drag of each seal is quite small, but when taken as a whole the impact of overall friction is considerable. In the racing arena, where sometimes a couple of horsepower can prove decisive, reductions in seal friction can be highly beneficial, particularly in high-rpm applications where losses increase exponentially with rotating speed. To combat friction, materials such as Teflon are used, which will be covered in greater depth below. Losses can, however, be caused by unforeseen circumstances.

A cross-section of the various different forms seals can take, depending on application (Courtesy of Repack-S)

In this particular case, during dyno testing an engine manufacturer noticed that measured engine power would drop erratically as rpm increased. It so happened that the seals manufacturer was on site at the time, and they suggested that it may be due to a sealing problem. The engine in question featured a dry sump and vacuum pump to help reduce power loss due to crankcase windage. Clearly, when a crankcase vacuum is desirable, the integrity of all of the seals – both static and dynamic – is paramount, so that the power required to pull a vacuum is as small as possible.

The problem was isolated to the crankshaft seal, which turned out to be too rigid to accommodate the very small degree of oscillation present in the crank's rotation as each cylinder fired. The seal in question was a standard Teflon lip seal, which while providing very low friction was also stiff. This meant it could not provide a consistent seal on the crank and consequently air could be drawn into the crankcase, reducing the level of vacuum and thus impacting power output.

The solution was to use a hybrid seal that featured a very thin layer of Teflon bonded to a nitrile rubber substrate. This way, the frictional losses could be kept to a minimum, but the additional flexibility of the rubber allowed the seal to conform to the tiny oscillations of the crank, providing a more consistent seal and eliminating the anomalies in engine power output.

These cases show just two areas where seal design can have a considerable impact on the operation of an engine. There is a plethora of other factors that need to be considered, but to cover them all is beyond the scope of this article.

Before moving on to the subject of material selection, it is worth noting that not all seal design considerations concern the mechanical performance. An example of this is the integration of flanges into the body of a seal. Many off-the-shelf seal designs feature a flange section, generally to add stiffness, but according to one manufacturer, including a flange can bring other benefits. The position of a seal on a shaft can often have an impact on its performance, so by including a flange the seal can be positioned exactly without specialist tools. In the words of one seal engineer, "With a flanged seal you can fit it by just tapping it into place until the flange sits flush against the case – which can be very useful if you are not servicing an engine under factory conditions."

Materials

Beyond ensuring that a seal is dimensioned correctly for its intended application, the choice of seal material is of equal if not greater importance for its overall effectiveness. The inside of a race engine is a very harsh environment, with seals being subject to extreme forces, temperature and chemical attack. For this reason, dedicated motorsport seals tend to be constructed from fluoropolymers, referred to generically as PTFE (polytetrafluoroethylene). These are favoured due to their resistance to temperature and chemical degradation as well as their low frictional properties, although in some cases nitrile rubber is still used where temperatures do not exceed 110 C.

PTFE was discovered by accident in 1938 by Dr Roy J Plunkett of Du Pont's Jackson laboratory in New Jersey, US. While investigating gases related to fluorinated refrigerants, he found that one sample left overnight in a pressurised storage cylinder had polymerised spontaneously to a white, waxy solid. This solid proved to have a unique composition with remarkable properties.

The molecular structure of PTFE is based on a linear chain of carbon atoms which are completely surrounded by fluorine atoms. These carbon-fluorine bonds are among the strongest occurring in organic compounds, giving PTFE excellent resistance to temperature and chemical degradation. The performance of PTFE was further increased in the 1990s with the development of radiation cross-linking of the molecules to improve the mechanical properties of the material in high-temperature applications.

One manufacturer consulted for this feature revealed that in applications where absolute consistency is key – for example in sealing pneumatic valves – careful attention needs to be paid to the base material used for seal construction. Two seals can look identical but have differing coefficients of thermal expansion, wear resistance and flexibility if the billets of PTFE they were made from were sourced from different suppliers. This is due to variations in the base powder stock and the sintering and curing process, among other factors. For these reasons, the manufacturer in question goes to the extent of producing its own raw materials in order to ensure it attains the level of consistency demanded in applications such as Formula One.

Developments in PTFE seals have been guided largely by new filler technology. Fillers are used to improve the overall mechanical performance of the seal, with a variety of materials being used to augment the basic material structure. Despite its remarkable properties pure, unfilled or virgin PTFE is inadequate for a number of more demanding engineering applications. In particular, its cold flow or creep behaviour precludes the use of PTFE in mechanical applications. Even at room temperature, PTFE experiences a significant deformation over time when it is subjected to a continuous load. Also, virgin PTFE has hardly any resilience and wears quickly, despite its low coefficient of friction.

Glass fibre is one of the most commonly used filler elements with a positive impact on the creep performance of PTFE, which is reduced at low and high temperatures. It also adds wear resistance and offers good compression strength. In higher end applications one finds glass fibre replaced by carbon fibres, which not only lower creep but increase flexibility as well as hardness. Other important benefits of carbon fibre in engine seals are a lower coefficient of thermal expansion and greater thermal conductivity.

Other filler materials are used to adjust the frictional properties of PTFE. For example, graphite-filled PTFE has one of the lowest coefficients of friction available while also having excellent wear properties, particularly against soft mating surfaces combined with high load-carrying capability in high-speed contact applications. Two other friction modifiers are bronze and molybdenum disulfide (MoS_2). Molybdenum disulphide increases the hardness and stiffness of PTFE while decreasing friction, and is normally used in conjunction with other filler materials such as carbon fibre.

Beyond these basic materials, seal manufacturers have developed their own special formulations but, owing to the competitive edge these provide, they were unwilling to divulge their exact make-up. The consensus is that these new types of filler allow less material to be used, thus increasing the proportion of PTFE in a seal and leading to lower friction levels.

On a final note, the opinion of one bespoke seal manufacturer is of some interest. Due to the high rate of development in motorsport it is often the case that the sealing technology used is not the absolute optimum it could be. In aerospace, for example, there may be a lead time of five years in which to develop the most durable, lightweight and low-friction compound possible; in racing, an engine manufacturer will settle for the best that is available at the time. For this reason, and combined with the fact that the high development costs of bespoke solutions can usually only be shouldered by large industry, seals for race engines will continue to be based on technologies developed in other industrial sectors.

Acknowledgements

The author would like to thank Chris Gregory at GST Racing Seals, Christoph Rodriguez at Repack-S and Barry Clough at Trelleborg for their assistance with this article. ■

SOME EXAMPLES OF SEALS SUPPLIERS

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