Produced by: GGB October 2020

Novel Low Friction, Machineable Metal-polymer Bearing for Lubricated Applications (in Fluid Power Systems)

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Abstract

Metal-polymer bearings have been relatively successful in replacing traditional leaded bronze or bi-metal bearings in many lubricated applications. Until recently however, PTFE based metal-polymer plain bearings were unable to match the assembled dimensional precision of metallic alloy bearings, thus restricting their use in those applications where control of the shaft clearance is critical for operational efficiency or reduced noise, vibration and harshness.

In an attempt to bridge this gap, GGB commissioned a project to develop a metal-polymer bearing solution that offers the possibility of being machined on installation for improved internal diameter control, whilst maintaining all the tribological benefits associated with the self-lubricious PTFE top layer. This paper shares GGB's development experience, highlighting the challenges faced and the lessons learned. In addition to GGB's internal validation testing that will be described, the unique characteristics and performance advantages of this new product concept will be highlighted using two case studies where metal alloy plain bearings have successfully been replaced.

These case studies will share customer feedback and experience following performance evaluation in the field by two key development partners, representing two different lubricated applications and markets, namely gear pumps and compressors.

Background

Fifty years after the invention of the first ever sel-flubricated metal-polymer plain bearing, their use continues to grow and find new applications in lubricated applications and fluid power systems. In many instances, these self-lubricating bearings have replaced traditional rolling element or metallic alloy bearings.

Their success in this field is largely attributed to the unique blend of tribological properties offered by the multi-layer composite structure shown in Figure 1, which consists of:

1. A metal backing, predominately steel
2. A sintered porous bronze layer of approximately 30% porosity filled with a specially formulated PTFE blend
3. A thin top layer of the same PTFE blend impregnated into the bronze, commonly referred to as the overlay.

Key bearing properties such as friction, wear, fatigue and erosion resistance are all largely determined by the filler choice and proportion.

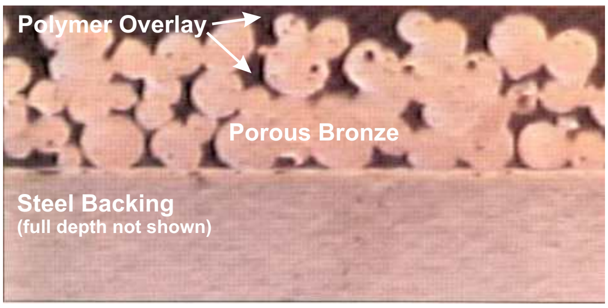

Figure 1: Typical cross section of a PTFE based metal polymer bearing

	Metal Alloy	Traditional Metal Polymer	Desired Solution
Friction	Poor	Good	Good
Dimensional Precision	Good	Poor	Good

Table 1: Friction and dimensional characteristics by bearing type

This material configuration is generally the preferred choice for design engineers due to the lower friction of the PTFE layer, compared with metal alloy bearings, and its ability to self-lubricate during periods of marginal or insufficient lubrication. Furthermore, the lower stiffness of this self-lubricious polymer top layer promotes the formation of the fluid film due to elasto hydro dynamic (EHD) effects and makes this type of bearing considerably more tolerant of shaft misalignments and edge loadings than its metal counterparts.

Despite these performance advantages, metal alloy plain bearings are still used extensively in applications where tight tolerances are required. The homogeneous composition of metal alloy bearings allows them to be machined in the assembly to a significant depth without affecting the performance of the sliding surface. By contrast, machining a conventional PTFE based metal polymer bearing has not been recommended because of the limited thickness of the PTFE layer, typically 5 – 25µm, and the performance risks associated with exposing high proportions of the underlying bronze. The general tradeoff between these product types, with respect to tolerances and friction, is summarized in Table 1.

Attempts to reduce ID variation of metal-polymer bearings have typically relied on secondary sizing techniques which involve insertion of a specially designed, oversized pin through the assembled bore to plastically reduce the bearing wall thickness and alter the diameter. This technique can however, with high pin interferences, present a possible risk to bearing performance when operating under aggressive conditions. It is always recommended that thorough validation testing is carried out if this technique is adopted.

With respect to compressors, for example, previous work has demonstrated that a significant level of burnishing can take place without a measurable reduction in wear life (1). The dimensional tolerances produced by this method, however, have historically not matched the precision of a machined metal alloy bushing.

In some applications, optimized performance can only be achieved through control of clearances.
Compressors manufactured with metal-polymer bushings have been shown to provide efficiency increases as high as 3% in comparison to metallic bearings of the same clearance level (2). Similar desires for improved dimensional tolerances have been expressed by gear pump manufacturers for both improved mechanical efficiency and reduced noise and vibration.

Project Detail

Recognizing these market requirements, GGB embarked on a pioneering development program to develop a low friction, metal-polymer bearing for use in oil lubricated applications that was capable of being machined after assembly for improved dimensional precision. A critical element of the development strategy was to leave intact a sufficient coating of filled PTFE on the surface after machining to ensure the aforementioned performance benefits of traditional metal polymer are maintained.

This project objective presented two key technical challenges that would require a delicate balance of material and process development:

Firstly, a means of producing a sufficiently thick PTFE layer above the porous bronze structure had to be found. GGB's standard processing technology, which relied on coagulation of PTFE aqueous dispersions and fillers to produce a wet, polymer blend that could be easily impregnated into the pores of the bronze, was limited to a maximum overlay thickness of 30µm. This restriction was a consequence of having to drive off the moisture and solvents within the paste and the associated risk of blistering above this thickness.

Preliminary calculations, based on application engineering experience with gear pumps, indicated that 100µm was the absolute minimum overlay thickness required to provide an adequate machining allowance and functional operating layer. The target design thickness of the functional operating layer after machining was defined to be 5 – 60µm.

The second challenge was to develop and optimize an appropriate PTFE and filler formulation that was not only compatible with the process method adopted, but that could be machined cleanly with minimum burrs and still offer a respectable bearing performance in oil with respect to wear, fatigue and erosion resistance.

The project, from concept to solution, followed a series of standard procedures and milestones associated with a disciplined stage gate process. GGB's standard development protocol consists of 6 distinct stages (See Figure 2).

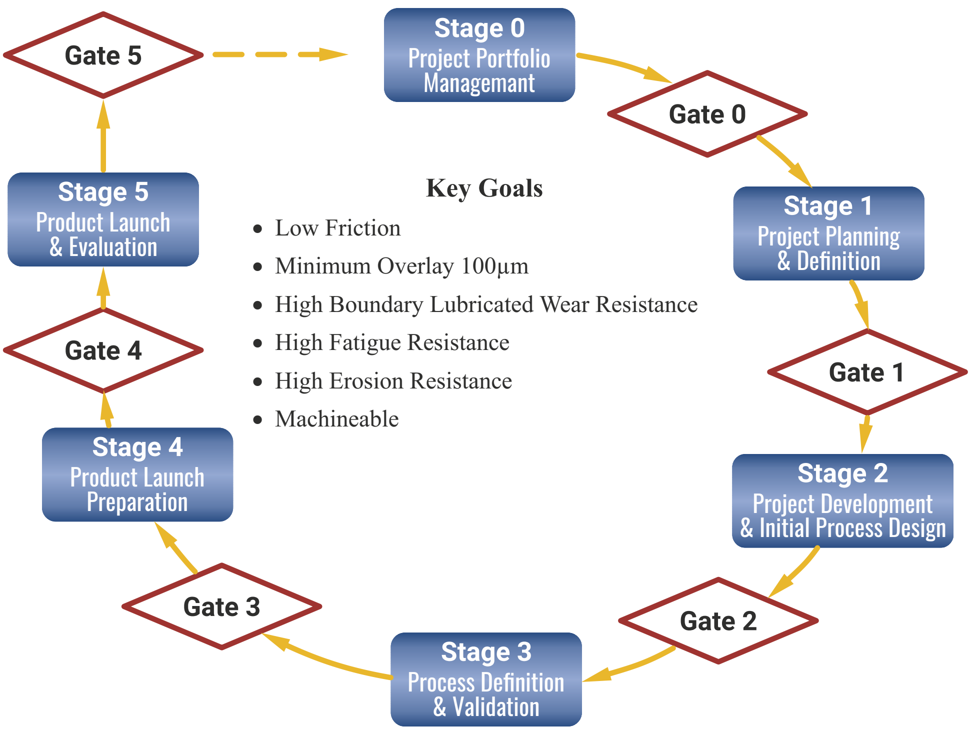

Figure 2: GGB's product development cycle and generic goals

Essentially, Stages 0 and 1 were concerned with initial project evaluation and planning. During this phase, the general project objectives were agreed and converted into specific, measurable development targets. In this instance, the minimum acceptable performance limits were set with respect to friction, wear, fatigue and erosion properties, each quantified and defined relative to the known performance of a reputable benchmark metal-polymer material which had been tested under GGB standard conditions. An 'equivalent' performance to this benchmark product was deemed a satisfactory goal in each case.

Other secondary product characteristics to be considered included chemical and temperature resistance, PTFE layer adhesion and the material's ability to be formed into a range of common bearing forms and geometries such as washers, cylindrical or flanged bushes.

With respect to the 'machineability' of the product, a number of challenges were noted. It was necessary to consider how to limit bronze exposure since the risk of seizure or reduced bearing life increases with exposed bronze. Also, it had to be verified that polymer thickness could be adequately controlled across the machined ID, or alternatively shown that thickness variation has no adverse impact on performance. Classic machining considerations such as the possibility of galling or tearing and its effect on surface finish or quality also had to be taken into account.

The principal development activities and intensive effort to identify, verify and validate a suitable material and process solution took place during Stages 2 and 3.

During the feasibility stage, all known PTFE processing methods were explored for their ability to permit thick layer formation. PTFE skiving appeared to be the most promising route, allowing the formation of continuouscured lengths of filled polymer tape. However, after considerable time and effort, this process was shown to be insufficiently robust due to the toughness of the tape and the difficulties to impregnate into the pores of the bronze. Either an insufficient depth of impregnation was achieved or excessive material stress resulted in surface blistering or crack formation along the top of the bronze layer. In both cases, these effects presented a potential risk of aterial delamination or galling during machining or bearing operation. After failing to eliminate these risks, the project appeared to stall, necessitating a complete review of its viability.

After deliberation, it was decided to initiate a collaborative partnership with a PTFE tape manufacturing specialist to develop and optimize a process for producing a highly filled PTFE tape in an uncured form. Uncured PTFE tapes possess significantly higher plasticity and flexibility, thereby enhancing their ability to be impregnated with minimum stress on the material. This approach clearly required a second process to cure the filled PTFE layer after impregnation and to optimize the molecular structure and tribological properties of the sliding surface.

Preliminary trials showed that the ease of tape impregnation was very sensitive to the formulation of the polymer blend. Several experimental blends were tried and tested, the chosen formulations being based on GGB's previous experience with effective filler packages for oil lubricated environments. Those candidates that were successfully impregnated were first subjected to laboratory machining trials on a lathe followed by tribological screening. One particular candidate stood out from the others, surpassing all tribological performance expectations. This composition comprised of a PTFE matrix filled with two other key ingredients, one of which was calcium fluoride, a reinforcing filler known to function effectively in oil and which is common to many of GGB's lubricated products.

After extensive testing and having verified the ability to produce material strip and manufacture bearings with a sufficient overlay thickness and quality, the material design was frozen. The project then passed to Stage 3 where the main focus was to establish and validate a robust, capable high volume material and bearing manufacturing process. This phase required considerable investment and modification of existing processing lines.

With the modified line in place, a series of studies were conducted to optimize the production of the composite strip in continuous coil form and to understand the complex interaction between and among key parameters such as line speed, temperature, applied pressure, tape thickness and tape tension on both the dimensional and tribological characteristics of the material. This was a lengthy process since each iteration required the manufacture and testing of a large number of material variants, across a wide range of test rigs and conditions.
After establishing the optimum process window, process robustness was demonstrated and validated by means of repetitive high volume material and bearing manufacturing trials, followed by extensive testing to confirm product stability.

Many unexpected problems and challenges arose regularly throughout the project but each time a plan was established to systematically address and resolve the issue. The only consequence was an ever expanding timeline.

Voice of the Customer

Despite an early indication from laboratory testing that this prototype solution had the potential to satisfy the project objectives, both with respect to bearing performance and its ability to be machined, it was recognized that an independent evaluation by a potential end user would provide invaluable intelligence and confirm whether GGB was on the right track.

For this purpose, GGB invited one major gear pump manufacturer and one major scroll compressor manufacturer to join the project as development partners to assess and help refine the product. Opportunistically, both customers were actively seeking alternative bearing solutions to their existing metal alloy bearings due to environmental pressure to eliminate lead.

These applications offered two extremely challenging, but vastly different, operating environments (see Table 2). Additionally, both used two distinctly different bearing geometries, representing small and large diameter parts.

	Scroll Compressor	Gear Pump
Bearing diameter [mm]	40 - 60	8 - 42
Load [MPa]	3 - 6	25 - 50
Speed [m/s]	8 - 11	2 - 5
Lubricant	Oil (2%) + Refrigerant	Oil
Clearance [µm]	70 - 100	25 - 50
Temperature [°C]	65 - 107	80 - 120

Table 2: Comparative operating conditions and bearing requirements

Case Study 1: Gear Pump Bearings

The gear pump (or motor) provides a compact, efficient, high-pressure unit that is ideal for many fluid power applications. The gear pump is simple in concept: two intermeshed gear rotors draw in the fluid on one side and force it out of the other. In consequence, these types of pumps are used in large numbers, particularly in the construction, agriculture, automotive, aerospace and mining industries. For example, in the automotive industry gear pumps are used in power steering systems, in construction and off-highway equipment and for tractor power take-off systems.

The performance of a gear pump depends largely on the design and dimensional precision of the gear rotors, the chambers in which they rotate and the bearings that support the rotors. Metal-polymer bearings are commonly used in high duty pumps, lubricated by the pumped fluid and operating under hydrodynamic conditions with very thin lubricant films.

Low wear rate is an obvious requirement, since wear affects the relative positioning of the gear rotors and hence the pump efficiency. In addition to the high specific bearing loads due to the pump delivery pressure, the bearing surface is also subjected to dynamic loading from the interaction of the gears, requiring adequate fatigue strength of the bearing material. A form of cavitation erosion of the bearingsurface can also occur. Ideally, the bearing must offer the right blend of such properties whilst maintaining very low friction characteristics.

The pump design selected was part of the new generation of 'silent' gear pumps that require critical control of certain bushing block dimensions to reduce noise, vibration and harshness. The assembled tolerances, which could not be satisfied with conventional thin layer PTFE metal-polymer bearings, are shown in Figure 3. The customer relied on the machining of four leaded bronze bearings, assembled in two aluminum binocular blocks, to give the necessary precision for supporting the gear rotors.

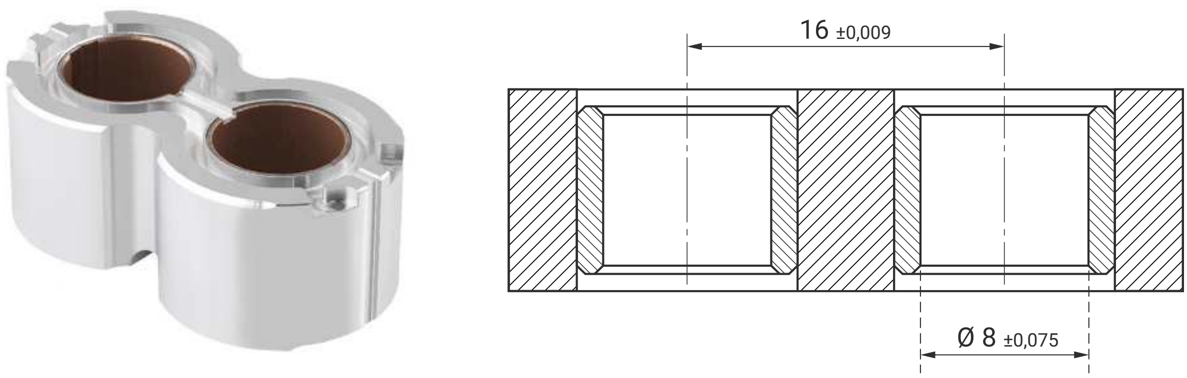

Figure 3. Critical dimensions and target tolerances on bushing block assembly

In this particular case, GGB had full responsibility for manufacturing and supplying the entire bushing block sub-assembly, so all bush assembly and machining experience was gained at first hand and under fully automated production conditions.

The crude form of the aluminum block is first machined and the bearings assembled. The internal diameter of each installed bearing is reamed simultaneously to size, after which two parallel grooves are cut. Finally, the exterior of the housing is then machined to its final size and form, relative to the bearing ID.

Using the standard machining set up and conditions for leaded bronze bearings, initial trials with GGB's machineable metal-polymer prototype were disappointing with respect to finished dimensions and quality. Among the issues were poor cylindricity, machined polymer swarf remaining attached to the bore and an uneven PTFE sliding layer around the bore with occasional localized exposure of bronze.

As a result, a study was initiated with a University department specializing in machining practices, to gain more experience and help establish recommended machining guidelines and tooling design for this type of product. Concurrently, an exercise was carried out by GGB process engineers on the bushing block automated machining and assembly line to optimise machining set up and conditions. These activities lead to each of the identified issues being systematically resolved, but it became evident that this metal-polymer solution was not going to be a simple 'drop in' replacement for any metal alloy bearing. This metal-polymer solution would require some process refinement and validation trials by the end user. In particular, special care must be given to tooling set up and alignment due to an overlay thickness of just 100μm.

To date, machining experience totals over four million assembled bushes (two million bushing blocks) for this particular application. The product concept and process has been proven capable of meeting all the customer's dimensional specifications. For an internal diameter tolerance of 0.015mm, a dispersion of 0.08mm is achieved, representing a Cpk of 1.67.

After machining, the bore surface roughness is typically 1.2 μm Ra. Although this is slightly higher than that expected from a metal alloy bearing, it presents no problems due to the soft, conformable and lubricious nature of the material.

The first laboratory testing of prototypes in the pump were sufficiently encouraging to capture the customer's interest and commitment to the development project. Extensive field testing thereafter by the customer confirmed the anticipated performance advantages in terms of friction improvements and superior seizure resistance compared with the leaded bronze, especially during start / stop conditions. It is believed that the lower modulus polymer layer provides a damping effect that has a noise reducing impact as well.

Case Study 2: Scroll Compressor Bearings

Scroll compressors are designed to compress air or refrigerant and as such are commonly used in commercial air conditioning systems, central heating pumps, and automotive air conditioners. The operating principle relies on relative motion between two spiral scrolls trapping and pumping pockets of fluid between the scrolls. To function efficiently, certain types of scroll design require extremely tight tolerances with respect to bore position and bearing clearance.

The chosen development partner used machined aluminum alloy bearings containing lead and were actively pursuing lead free alternatives. Changes in regulations for refrigerants were requiring a more robust bearing performance to deal with the increased pressures. Since metal alloy offerings had difficulty handling these loads, metal-polymer bearings were considered by the design engineers. However, they had found that poor efficiency resulting from loose tolerances remained the principle hurdle that had to be overcome in order to meet governmental SEER ratings.

In addition, it was specified that the bearing solution must be:

- Compatible with the oil and refrigerant
- Capable of surviving three arduous test regimes:
- 1. Repetitive dry start testing with no lubrication (heavy contact for short periods)
- 2. Boundary / mixed film lubrication (light contact for extended duration)
- 3. Hydrodynamic testing (ideal condition)
- Fatigue resistant
- Erosion resistant
- Seizure resistant
- Tolerant of debris and edge loading

The two upper bearings supporting the main housing and orbiting scroll of a 15 Ton compressor were selected initially for prototype testing. The general design and bearing positions are illustrated in Figure 4. Successful results during early testing inspired our partner to expand the trials to the higher loaded 30 Ton compressor also.

Contrary to case study 1, machining in this case was not automated and relied on a manual lathe machining process carried out by the customer.

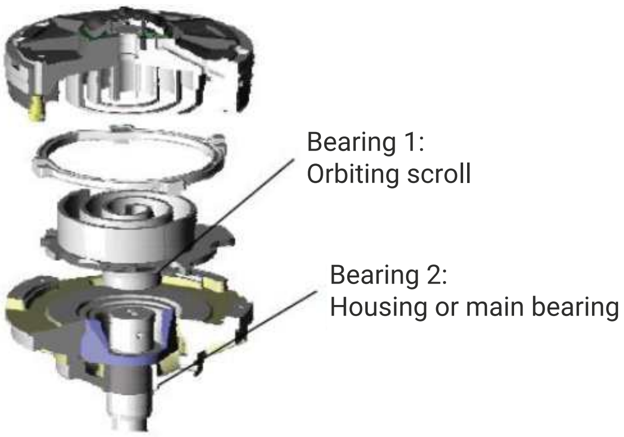

Figure 4: Scroll compressor concept and test bearing locations

Over a period of two years, this customer carried out a series of rigorous laboratory compressor tests, pushing the prototypes to their limits in order to investigate the most common potential failure modes. Although, purposely aggressive and accelerated testing showed that fatigue damage and erosion were possible in this environment, it was shown that these were not progressive, once initiated.

Under standard conditions, this material was found to excel in all areas.

Product Attributes

The original product concept has evolved continuously throughout the eight year project, as incremental refinements were systematically made following valuable feedback and recommendations from our development partners.

The resulting product, called DTS10™, clearly extends the performance capability of traditional metal polymer bearing technology and, due to its dimensional tolerance, provides a viable alternative in applications heretofore dominated by metal alloy bearings.

The DTS10™ bearing structure (see figure 5) provides a nominal overlay thickness of 0.12 mm (0.1 mm minimum) which can, under carefully controlled conditions, be machined to tight tolerances without sacrificing the usual benefits of metal-polymer bearing.

Figure 5: Cross section structure of DTS10 ™

Bearing Performance Attributes

Standard GGB test rigs and test conditions were used to evaluate DTS10™ performance. All key bearing properties were measured and compared with those of the reference metal-polymer product defined in the original project objectives. Where possible, the influence of machining on the material properties was verified also. In each case, no significant or negative performance impact was observed when recommended machining conditions and practices were followed.

Friction

Tribometer testing under a range of conditions, both dry and oil lubricated, confirmed low levels of friction consistent with a sliding surface whose principle ingredient is the natural lubricant PTFE.

Figures 6 and 7 compare friction of DTS10™ with increasing load with that of a standard bi-metallic bearing material under both dry and lubricated conditions respectively.

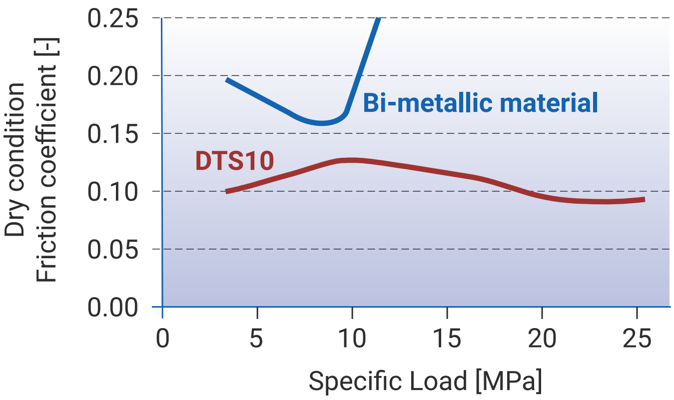

Figure 6: Friction - load relationship for DTS10™ and a standard bi-metallic baring material, under dry conditions.

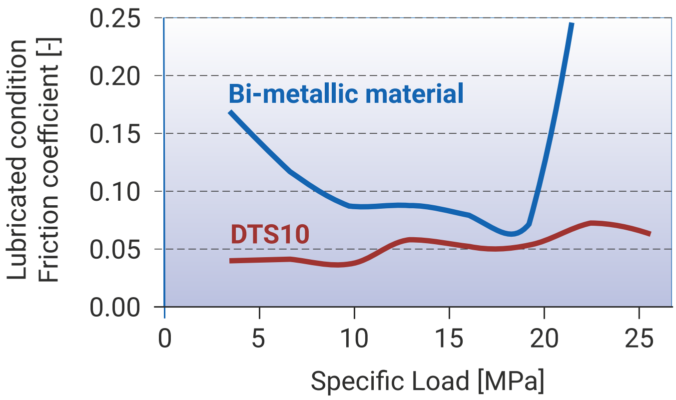

Figure 7: Friction - load relationship for DTS10™ and a standard bi-metallic bearing material, under oil lubricated conditions

In each case, the lower friction, higher load capacity and improved seizure resistance associated with the self-lubricating metal-polymer bearing are evident.

The friction compared with the target metal-polymer reference, as defined in project objectives, is shown in Figure 8.

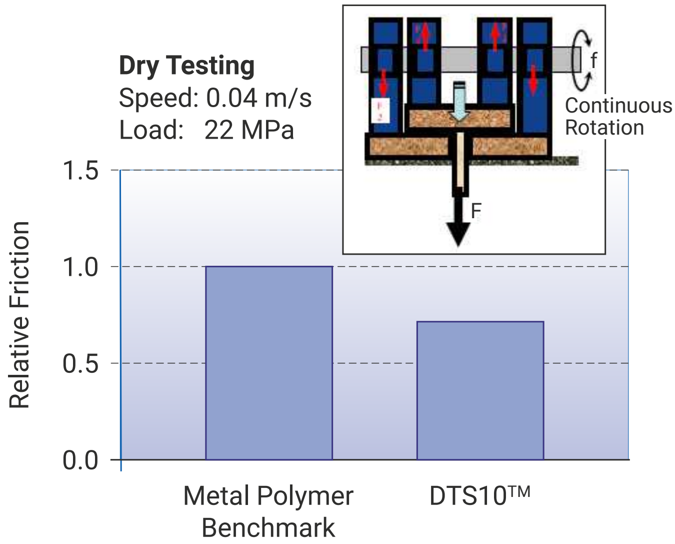

Figure 8: Relative friction (dry) between DTS10™ and Metal-polymer Benchmark performance

Boundary Lubricated Wear Resistance

The wear resistance and durability of DTS10™ were found to be significantly superior to the current industry metal-polymer benchmark in both machined and nonmachined form. The boundary lubricated wear resistance of DTS10™ is compared with the metal polymer benchmark performance in Figure 9.

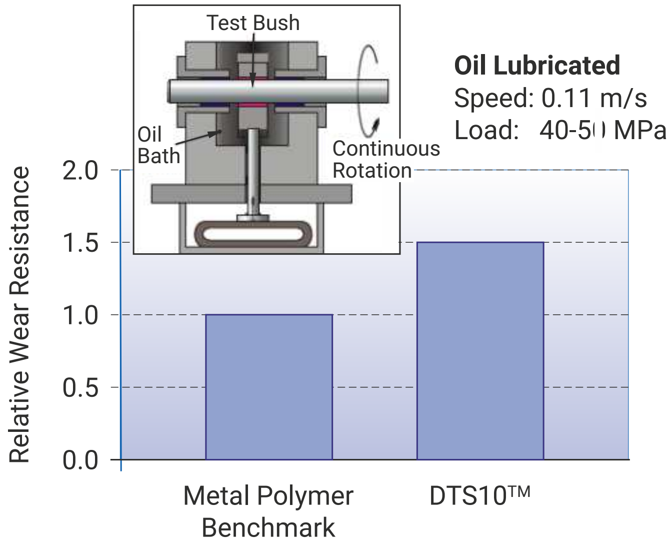

Figure 9: Relative wear resistance under steady load, boundary lubricated conditions

Fatigue Resistance

Fatigue resistance is especially important in gear pumps and scroll compressors where bearings are subjected to high frequency dynamic loads in oil. Under this regime, the resistance to fatigue damage was found to be exceptionally high for DTS10™, enduring over 16 million cycles before any signs of damage. This is approximately 4 times higher than the current metal polymer standard.

The fatigue damage of DTS10™ relative to the metal polymer benchmark performance is shown in figure 10.

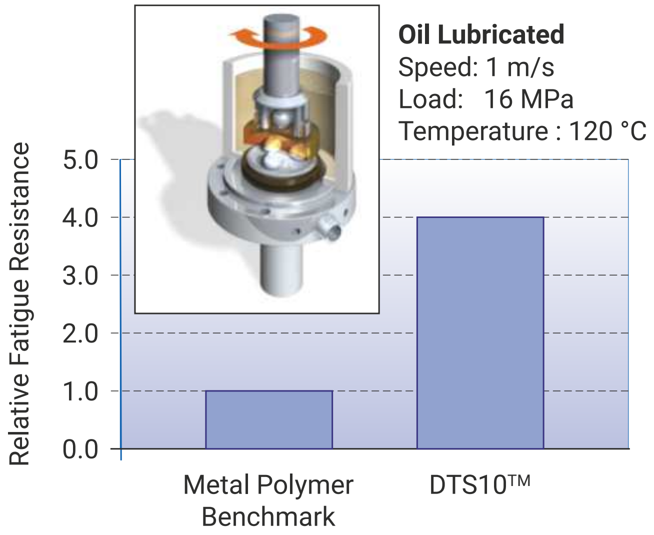

Figure 10: Relative fatigue resistance between DTS10™ and the metal-polymer benchmark performance

Cavitation Erosion Resistance

The bearing's ability to resist cavitation erosion was measured and compared with that of the project benchmark metal-polymer product.

The relative cavitation erosion resistance is shown in Figure 11.

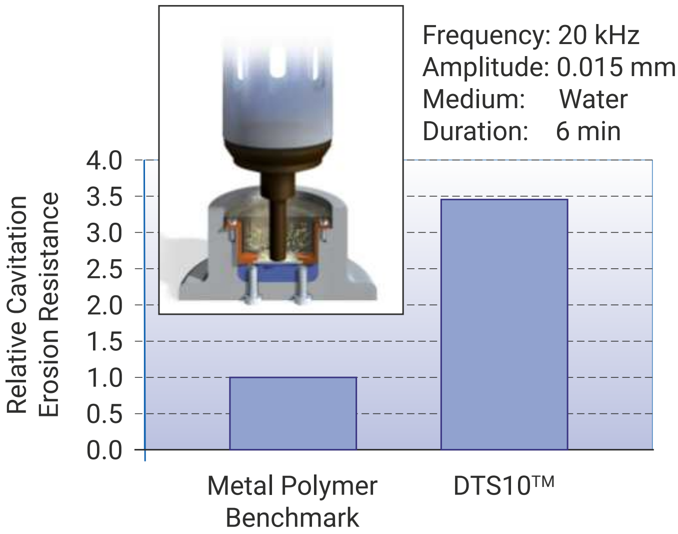

Figure 11: Relative cavitation erosion resistance between DTS10™ and the metal-polymer benchmark performance

Corrosion Resistance

Aggressive oils, especially those containing high levels of sulphur, are known to be capable of chemically attacking the bronze in bearings. Laboratory corrosion testing of DTS10™, using a particularly aggressive standard test oil heated to 140ºC, indicated that this product offers a significant improvement in chemical resistance compared to most other metal-polymer products. This was also true of DTS10™ in its machined form.

Figures 12a – 12c show images comparing the level of corrosion found in DTS10™ with other reference bearing materials after 100 hours of exposure to the heated oil.

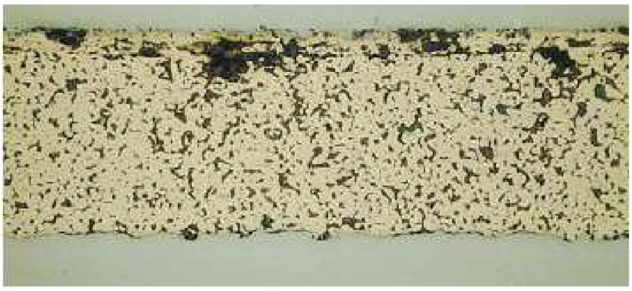

Fig. 12a: Industry standard bi-metallic bearing after corrosion testing

Fig. 12b. Metal-polymer benchmark bearing after corrosion testing

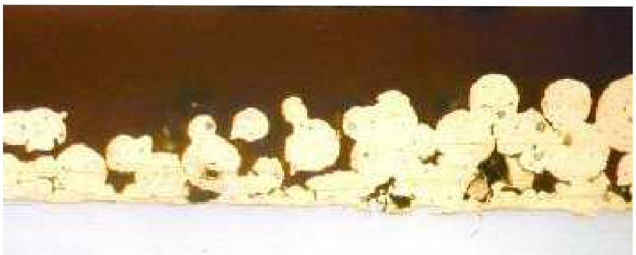

Figure 12c. DTS 10™ after corrosion testing

GGB testing indicates that DTS10™ has exceeded all of the original project performance metrics, consistently outperforming the current best PTFE industry benchmark product. Customer testing and feedback in gear pumps and compressors also support this conclusion. This enhanced bearing performance is the result of both the carefully designed formulation and a special proprietary processing technique employed during the preparation of the material blend.

Machining Characteristics

GGB and customer machining trials have confirmed that the material is compatible with most standard machining processes, including turning, broaching, reaming and milling. In each case, investigative trials have helped establish recommended procedures for each process. Studies have shown that surface roughness is quite sensitive to machining conditions. The effect of varying tool feed-rates, for example, can be clearly seen in Figure 13. It was subsequently shown that rougher surfaces may result in a slightly higher start up friction.

However, the surface would be quickly modified during run in with a corresponding return to the optimum friction level. No other effect of surface roughness was identified.

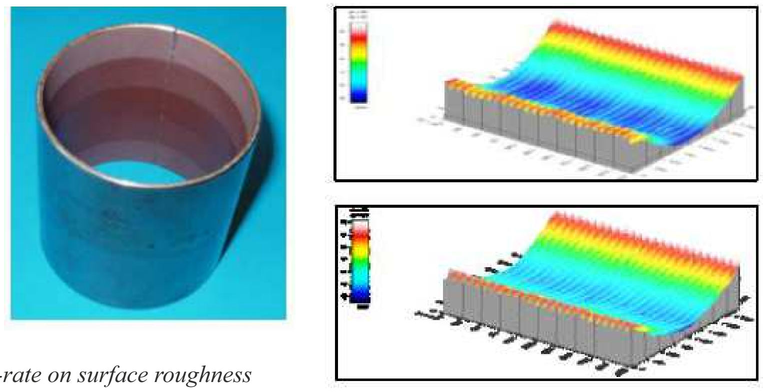

Figure 13. Influence of tool feed-rate on surface roughness

The low thermal conductivity of fluoropolymers, such as PTFE, can cause heating of the polymer material and tool during a high speed cutting operation. This can cause deformation of the PTFE and excessive wear of the tools. The use of a lubricant during machining is therefore considered critical to avoid such overheating effects. Also, to minimise tooling wear, PCD (polycrystalline diamond) or coated carbide (K10) tooling is recommended.
Machining the bore of DTS10™ bearings has been shown to significantly improve their concentricity. Trials have shown that the roundness of the assembled bearing can be as much as 16 µm, but after machining can be as little as 2µm.

Lessons Learned

GGB consider this project to be a success since the resulting product has been shown to meet or surpass all of its originally agreed project objectives. Nevertheless, there are always lessons to be learned from reflecting on the overall management experience. For this purpose, Stage 5 of GGB's development protocol includes a routine review.

The project served to highlight the enormous benefits of collaborating with third party partners, whether an end user or subject matter expert. Had GGB been unwilling to work with other PTFE processing experts, some of the technical barriers may never have been surmounted and the project killed at an early stage.

Similarly, if customers had not provided early feedback identifying product weaknesses in time for them to be resolved, the product might have been launched prematurely for its intended applications. This in turn might have led to extensive post-launch debugging or failure in the market. In reality however, the strengths and limitations of the product are well known in advance of launch, and can be communicated openly with the customer.

The nominal overlay thickness of 120 µm has been demonstrated to be a feasible level for machining if sufficient care and control is taken. However, it is recognized that this may not be compatible with every customer's machining capabilities. Therefore, it will be necessary to work with customers' engineers to optimize the design and machining setup. With this potential limitation, the pursuit of higher overlay thicknesses will continue.

The project, originally estimated at four years to find and optimize a solution, actually took eight years for a number of reasons, including overly optimistic planning and under-estimation of the technical issues. Consequently, on several occasions, the future of the project appeared to be jeopardy, but the market need and the determination and confidence of the team to find solutions was sufficiently convincing for management to continue supporting the project. GGB's stage gate process and its regular reviews was, for this purpose, especially effective for ensuring proper communication and regular debate on revised activities and timing proposals.

It is believed that the proprietary processing technology developed for DTS10™ and the experience gained will now provide a platform for the next generation of higher performance bearings for other operating environments, including those which are non-lubricated.

Conclusion

The goal of the project was to develop a polymer solution that combined the performance benefits of metal-polymer bearings with the dimensional precision of traditional bi-metallic journal bearings. This goal has effectively been met with the development and launch of DTS10™, a bearing that exploits all the advantages of the conventional metal-polymer composite structure but, having a specially formulated, thick PTFE overlay, can be machined on installation to provide improved control of assembled tolerances. The bush is designed to be assembled into a rigid housing and have its internal diameter machined to leave between 5 - 60µm of lubricious polymer above the bronze.

The formulation of the polymer overlay has been specifically tailored for operation in lubricated applications. Testing by GGB and field trials in gear pumps and scroll compressors have confirmed that all performance goals have been met. The coefficient of friction is very low, consistent with a PTFE lubricant. This translates to exceptional seizure resistance and improved operational efficiency in any fluid power system. In addition, the material possesses an impressive resistance to chemical attack, fatigue and cavitation erosion damage, all important properties for a bearing operating in an aggressive oil lubricated environment. These attributes, together with its machineability, promise to expand metal-polymer bearings into other new applications within the fluid power industry.

Significantly, the two end users who participated in the project have approved and adopted this solution in their gear pumps and scroll compressors and are looking to exploit the benefits further in future new projects.

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Definitions, Acronyms, Abbreviations

EHD: Elastohydrodynamic

ID: Internal Diameter

PTFE: Polytetrafluoroethylene

SEER: Seasonal Energy Efficiency Ratio

DTS10: DTS10 is a trademark of GGB

About GGB

GGB helps create a world of motion with minimal frictional loss through plain bearing and surface engineering technologies. With R&D, testing and production facilities in the United States, Germany, France, Brazil, Slovakia and China, GGB partners with customers worldwide on customized tribological design solutions that are efficient and environmentally sustainable. GGB's engineers bring their expertise and passion for tribology to a wide range of industries, including automotive, aerospace and industrial manufacturing. To learn more about GGB's coatings and other surface engineering solutions, visit www.ggbearings.com.

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