

THE USE OF ENGINEERING THERMOPLASTICS FOR CENTRIFUGAL COMPRESSOR LABYRINTHS

by

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ABSTRACT

The use of engineering thermoplastics is increasing rapidly in today's turbomachinery industry. The primary use of these thermoplastics has been as a material upgrade from aluminum for centrifugal compressor labyrinths. With proper application, substantial compressor efficiency improvements can be achieved by lowering seal leakage. Other benefits include increased reliability by reducing shaft damage during hard rubs and by allowing an alternate material selection for applications where the existing aluminum is attacked by the process. These aspects of the thermoplastic's application are addressed. Other materials used for their abrasibility properties (such as TFE) will not be covered.

INTRODUCTION

The specific application of poly-ether-ether-ketone (PEEK) and poly-amide-imide (PAI) are covered as examples of the engineering thermoplastics in use. Important data to evaluate are presented with a short discussion on some critical thermoplastic properties. Forthwith, the term polymer is used to refer to both PAI and PEEK.

The basic benefits afforded by the proper application of the polymer are discussed. This covers both efficiency improvements (by allowing close running seal clearances), and reliability improvements (due to the forgiveness of the polymer relative to aluminum during a rotor to stator rub.) A short discussion on polymer use to address corrosion problems is also included.

Next, a brief discussion on the engineering of the labyrinth for specific applications is covered. Most of the thermoplastics in use today have coefficients of linear thermal expansion (CLTE) much greater than the material they are replacing (usually aluminum). Since the newly designed polymer seals are installed with tighter running clearances, the calculation of the thermal growth of the material becomes very critical to a successful application. This discussion will include labyrinth tooth design and design clearances.

Also of importance to proper applications are stresses in the part due to pressure area forces, and interference at the seal fit area due to thermal growth of the part. Polymers are not as strong as aluminum, so careful attention to component stress levels is required. A discussion on material strength drop off at elevated temperatures is included. Another area discussed in this section is chemical compatibility (of the polymer to the process); however, since this is an application-specific topic, a detailed discussion will not be attempted. It is important to understand that chemical compatibility needs to be researched for every application.

Labyrinth seal impact on rotordynamics is also covered. Included is coverage on clearance effects, tooth location (on rotor or on stator), swirl break application and alternate seal configurations. This is a very brief overview added to answer direct concerns involved with polymer seal upgrades.

Some problem installations, applications, and startups are then discussed. The cases covered include labyrinth failure due to chemical incompatibility, improper installation, improper startup procedure, and improper mechanical application.

Finally, several successful case histories are presented where the application of a thermoplastic has significantly increased machine efficiency. These case histories are pulled from the ammonia, chemical, and refining industries, showing the wide acceptance of these materials. Additionally, reduced compressor damage due to other component failure (areas where the aluminum seals would have severely damaged the shaft) are discussed.

THERMOPLASTICS

Most readers are probably familiar (to some extent) with poly-ether-ether-ketone (PEEK) or PEEK based products. Another thermoplastic increasingly being used is poly-amide-imide (PAI). Thermoplastics can be broken down into two distinct groups [1, 2]; crystalline (such as PEEK) and amorphous (such as PAI) polymers. A discussion on the differences between these polymer types is included in the following sections.

It is also important to note that there are several common polymer processing options [2]. The most common are injection molding, extrusion molding and compression molding. Compression molded polymers are covered exclusively herein, due to the need for the large billet sizes required for labyrinth seals. Of the three process methods listed, compression molding offers the least mechanical strength (it is about half that of the same mix of the injection molded polymer). This makes it important,

when considering polymers for an application, that compression molded data are evaluated for all polymers under consideration.

Thermoplastics are often compared by evaluating various properties such as heat deflection temperature (HDT) and glass transition temperatures (T_g). These properties, along with strength data, can be combined to yield a maximum continued use temperature. Other factors to consider with thermoplastics include chemical compatibility and moisture absorption.

Heat Deflection Temperature (HDT) [1, 2]

This is a value obtained from an ASTM test (D648), during which a bending specimen is subjected to a load causing an outer fiber stress of 66 or 264 psi, while the temperature is increased. The temperature corresponding to an additional specimen deflection of 10 mil is the HDT (sometimes referred to as the distortion temperature under load, or DTUL.) The HDT by itself is an impractical value to directly apply, but it can be useful in comparing various thermoplastics.

The HDT for most thermoplastics is given at the 264 psi condition. It is important to note this, so a fair comparison can be made.

Glass Transition Temperature (T_g) (1)

The T_g is the temperature at which the polymer begins to change properties very rapidly. Strength drops off considerably, the thermal expansion increases, the material loses "memory," and other properties change significantly. Basically, operation above the T_g is not recommended for a compressor labyrinth.

Moisture Absorption [3]

PEEK moisture absorption is negligible whereas PAI does absorb moisture and can grow as much as two percent dimensionally (up to five percent by weight.) It is always best to protect finished parts from moisture prior to installation in the compressor. Moisture absorption from the process is a possibility, but it has been found to be negligible. Seals, in service for a year in an air compressor in the Gulf Coast area, rolled right out, implying negligible part growth despite prolonged exposure to high-humidity air. The leakage flow across the part may have set up a boundary layer that acted to isolate the seal from process moisture. The rate of absorption is also rather low, testing shows that it takes PAI several months immersed in 180°F water to fully soak. Lastly, moisture absorption does have a small effect on the polymers mechanical properties, this should be accounted for in any analysis work.

Chemical Compatibility

PEEK based materials are more compatible with a variety of chemicals than the PAI products. However, about 85 percent of the compressors investigated have processes that are compatible with both materials. It is important to evaluate the compatibility of the material not only with the process (including any recycle streams), but with any other chemical it may come into contact with (such as wash oils). A more thorough discussion on this topic will be presented later.

An informal comparison is shown in Table 1 of PAI with PEEK. Note that the data presented is for "friction and wear" grades (filled with graphite and/or PTFE), which are preferred for labyrinth applications. These thermoplastics can be filled with other materials (glass for instance) to increase strength and HDT, but they become very damaging during a hard rub in a labyrinth application. The base material controls the T_g ; therefore, filling PEEK or PAI with other materials will not increase the T_g .

The above is a very short discussion on thermoplastics. The intent was to supply enough information for background purposes.

Table 1. Selected Properties of PAI and PEEK.

Engineering Thermoplastics

1. PolyAmide-Imide (PAI)
 - ▶ Heat Deflection: 539 deg F
 - ▶ Glass Transition: 565 deg F
 - ▶ Maximum Use Temperature: 470 deg F
 - ▶ Moisture Absorption: 5% by weight
 - ▶ 2% by size
 - ▶ Chemical Compatibility: Moderate
2. PEEK
 - ▶ Heat Deflection: 594 deg F
 - ▶ Glass Transition: 280-300 deg F
 - ▶ Maximum Use Temperature: 250 deg F
 - ▶ Moisture Absorption: Negligible
 - ▶ Chemical Compatibility: Excellent

es. The data presented should be evaluated as minimums for all labyrinth applications.

BENEFITS

With proper application, design, and use, thermoplastic labyrinths can increase both compressor efficiency and reliability. Running with tighter clearances will have a direct impact on seal efficiency. Thermoplastic seals will maintain these tighter clearances, even through startups and normal transients, without damaging the shafting.

Efficiency

Typical labyrinth tooth designs are shown in Figure 1. Note that the design installed clearance of the polymer teeth is tighter than the aluminum teeth. Shaft to seal contact is shown in Figure 2 (passing through a critical speed for example). Note that the polymer tooth, which is angled, will deflect with the shaft (similar to a cantilever) while the aluminum tooth will "mushroom" over. Once through the critical (Figure 3), the polymer tooth, by benefit of the material's "memory" (due to a relatively low modulus), will return to its original shape while the aluminum tooth remains damaged. Also, note the possible scoring of the shaft by the galling action of the aluminum on the steel shafting.

Reducing leakage area and maintaining these reduced leakage areas is the main benefit afforded by the polymer labyrinth. As

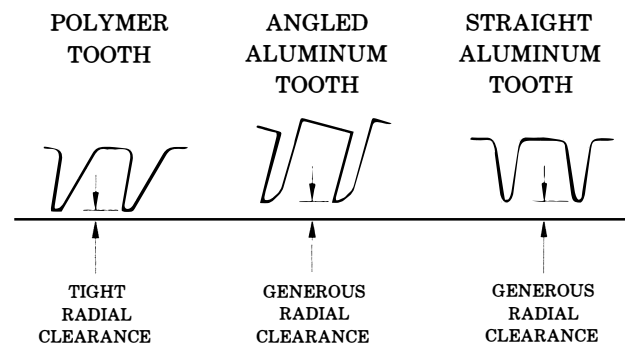


Figure 1. Typical Labyrinth Tooth Designs. (Note the tighter design clearance with the polymer tooth.)

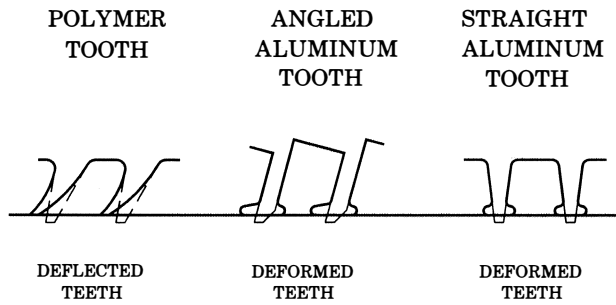


Figure 2. Labyrinth Tooth Deformation During a Rub. (Note that the aluminum teeth “mushroom” over while the polymer tooth deflects with the shaft.)

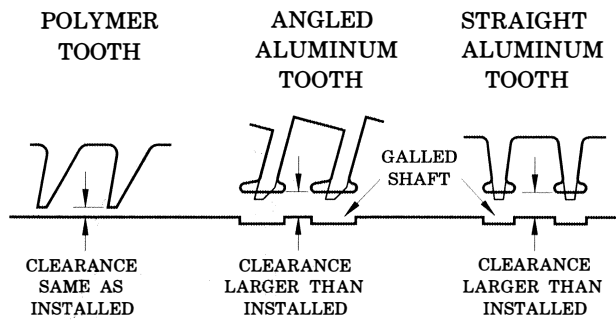


Figure 3. Labyrinth Tooth Profile After a Rub. (Note the permanently deformed aluminum teeth and the polymer tooth returned to original shape. Also note the potential galling characteristics of aluminum on steel.)

will be demonstrated in a later section, compressor efficiency gains of one-half to one percent per wheel can be expected in most upgrades. Certainly calculations utilizing improvement predictions of one-fourth to one-half percent per wheel should be sufficient to justify an upgrade of this type.

Note that if the balance piston seal is included in the upgrade, the higher of the two numbers should be used. Whereas, if the balance piston seal is not going to be part of the upgrade, the lower of the two numbers should be used. It has been found, in one instance where the PAI balance piston seal was removed, that the machine efficiency gain was reduced by half. This specific case will be discussed later.

Designing closer running seals that will hold their clearance without fear of damaging the shaft is the basic reason for upgrading to thermoplastic labyrinths. Of course the thermoplastic teeth will abrade, especially during a sustained hard rub, but the loss of clearance will be insignificant compared to the original aluminum seal clearances.

ENGINEERING

The proper engineering of thermoplastic labyrinths is paramount to a successful upgrade. The seals normally considered in an upgrade are illustrated in Figure 4 [4]. These include the shaft labys, the eye labys, the balance piston laby, and the compressor end wall seals. The arrows denote leakage flow paths that are used to determine the direction to rake the teeth.

Thermal Expansion

Perhaps the most important step in engineering these seals pertains to the thermal expansion calculations. Since most thermoplastics have high coefficients of linear thermal expansion (CLTE), and since the seal bores are being designed with

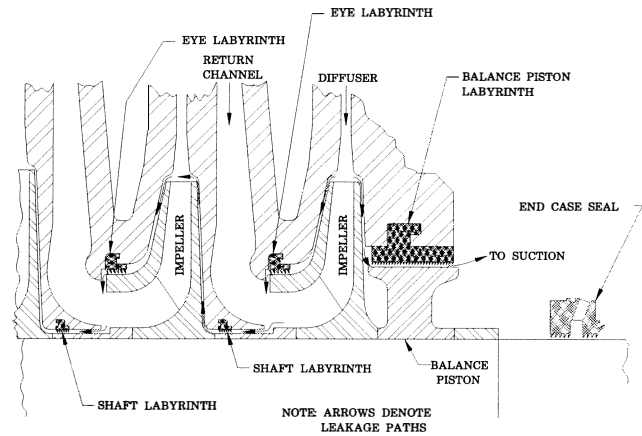
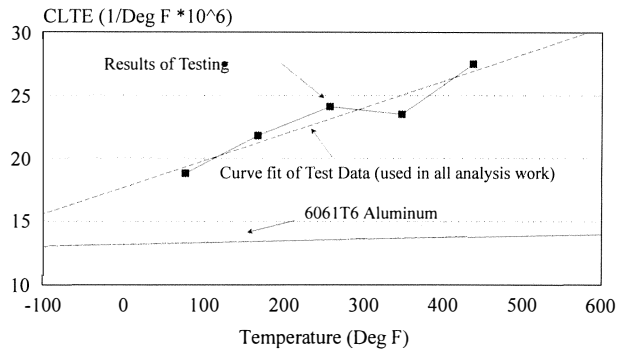


Figure 4. Labyrinth Seals Considered in a Typical Upgrade. (Also shown are typical leakage paths.)

reduced clearances, it is important to calculate the hot operating clearance of each seal.

A plot is shown in Figure 5 of the CLTE vs temperature for a PAI material. Note that the aluminum material being replaced (usually 6061T6) has a fairly constant CLTE of 13-14 micro in/in/°F. The CLTE for the PAI material starts at about 18 at room temperature and approaches 28 at its maximum use temperature. Proper design will account for the thermally imposed “crush” of the seal in its holder (considering the expansion of the seal and the holder), the resulting closing up of the bore of the seal, the thermal and centrifugal growth of the sealing surface, and all appropriate tolerances.



CLTE: Coefficient of Linear Thermal Expansion

Figure 5. Poly-Amide-Imide Coefficient of Linear Thermal Expansion Vs Temperature. (Note how the CLTE of the PAI increases significantly with increasing temperature.)

Design

Shown in Figure 6 are the operating clearance guidelines used at the author’s company. Basically, the minimum operating clearance of the seal is made to equal that of the journal bearing clearances in the machine. This “rule of thumb” has worked well in that it ensures adequate clearance between the rotating and stationary parts on startup and keeps seal clearances tied to bearing clearances, which are usually related to the compressor’s size and speed. In most instances, this results in closing up the cold installed seal clearances by 25 to 75 percent.

Also illustrated in Figure 6 is an interlocking seal where there are both rotating and stationary teeth. As will be shown later,

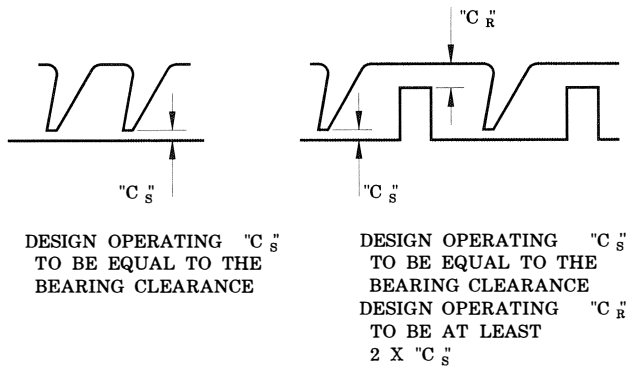


Figure 6. Polymer Labyrinth Clearance Design Guidelines.

these thermoplastics do not fare well when used in smooth bore applications with rotating teeth. Therefore the author's company doubles the clearance between the rotating teeth and the smooth root in the polymer seal, while maintaining the tighter clearance between the stationary polymer tooth and the smooth rotating surface as described in the rule of thumb above.

A photo of an interlocking style balance piston seal is shown in Figure 7. Note the rake of the teeth and the tooth spacing. Rotating teeth on the balance drum ride in between the polymer teeth. As discussed above the clearance for the rotating teeth is twice that of the polymer teeth.

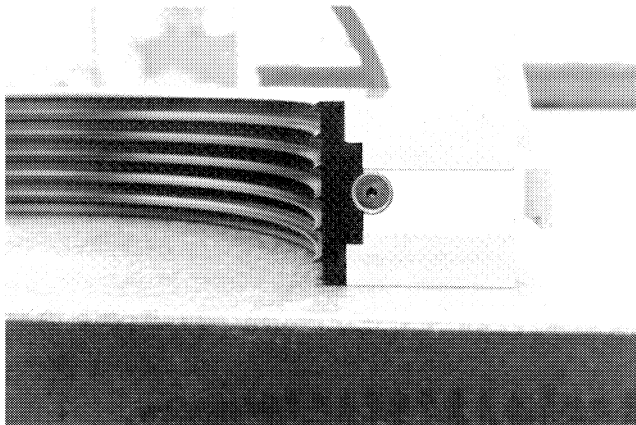


Figure 7. Example of Balance Piston seal for an "Interlocking" Tooth Configuration. The polymer labyrinth is shown inserted into an aluminum holder.

The seal in Figure 7 is also shown inserted into an aluminum holder. The aluminum seal being replaced was not inserted. The upgraded seal was inserted to reduce cost (the thermoplastic is more expensive than the aluminum) and to improve reliability (the lower profile polymer portion reduces pressure-area forces on the polymer insert.)

Some labyrinth tooth design notations are shown in Figure 8. As shown, raking the tooth against flow promotes turbulence between the teeth. This turbulence acts to retard leakage flow. Raking the teeth also sets up a "cantilevered" tooth, that can deflect during a rub, as described earlier. Other areas to note is that the pitch is set about equal to the tooth height and there are generous radii in the tooth root area.

It has been found [5] that the tooth thickness does not have much of an effect on laby performance. This allows a thicker

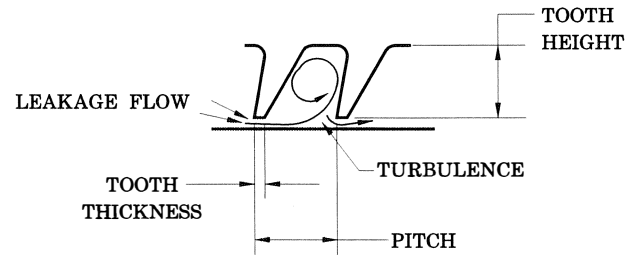


Figure 8. Labyrinth Nomenclature.

tooth which will also be a tougher tooth. The author's company currently uses a tooth tip thickness of 20-25 mil.

Of course, closing up clearances directly reduces the leakage area and the leakage flow. Just as important, however, is the seal's "clearance integrity;" these reduced clearances must be maintained even through rotor to stator contact (as discussed earlier).

Stress Analysis

Since thermoplastics are usually weaker than the aluminum being replaced, it is important to look at stress levels in highly stressed parts. This normally applies to balance piston seals and center seals (used in back to back compressors), where high pressure drops and their associated pressure-area forces are present.

Strength vs temperature is plotted in Figure 9 for a PAI material and 6061T6 aluminum. Note that at lower temperatures the PAI is considerably weaker than the aluminum while at higher temperatures the aluminum strength approaches that of the PAI. Two points not covered on this curve are thermal aging and stress concentration effects.

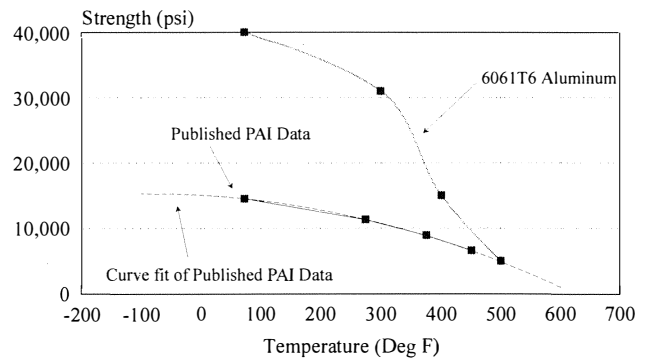


Figure 9. Strength Vs Temperature for PAI and Aluminum.

Thermoplastics lose strength when subjected to elevated temperatures over a prolonged period of time [6]. This effect is referred to as thermal aging. For instance, PAI loses 40 to 45 percent of its strength when subjected to its maximum use temperature (470°F) over several years (three to five years). This effect needs to be considered in all stress analyses.

Most thermoplastics are brittle compared to aluminum. As such, stress riser areas need to be carefully evaluated when thermoplastics are applied. Proper fillets and undercuts need to be designed into parts subjected to high stress levels. Stress concentration factors need to be incorporated in all stress analyses. Aluminum is much more ductile, lessening the concern over stress riser areas.

Rotordynamics

It has been well documented that labyrinth seals do directly contribute to the rotordynamic performance of a centrifugal compressor [7]. Basically the *axial* leakage flow contribution is to add damping to the rotor system. This is normally a beneficial property both from stability and response to unbalance concerns. However, the *circumferential* flow (swirl) has the effect of causing relatively high cross coupled stiffness coefficients, which often have a much greater impact than the damping. Cross coupled stiffness is a destabilizing force which is undesirable in a centrifugal compressor.

Reducing the circumferential swirl velocity will directly act to improve the seals influence on rotordynamics. This is often done with high visibility seals such as center seals and balance piston seals by adding a swirl break which acts to break up the gas swirl prior to entering the seal [7, 8].

Another way to reduce the circumferential swirl flow is to change the seal to a honeycomb configuration where rotating teeth seal against a honeycomb stator. This was done on the space shuttle main engine (SSME), high pressure oxygen turbo-pump (HPOTP) [9] to solve a stability problem. The honeycomb pattern acts to reduce the circumferential flow without sacrificing seal efficiency.

It is the author's opinion that no honeycomb seal should be eliminated from a compressor without first considering the impact on rotordynamics. The ability to accurately calculate rotordynamic coefficients for honeycomb seals is improving [10].

As far as the upgraded labyrinth impact on rotordynamics is concerned, it has been found that the specific labyrinth modifications, discussed earlier, have a minimal impact on the seal's stiffness and damping properties. Indeed, the closing up of clearances has been found to improve a given seals impact on system stability [11]. Long seals with high pressure drops at high modal displacement locations, such as center seals, should be evaluated on a per seal basis.

A rotordynamics study of the compressor may be warranted if there has been a history of instability or high sensitivity to unbalance. The impact of the seal design on the rotordynamics of the machine should be investigated, so as to not aggravate an existing problem.

Also, with compressors that exhibit very high amplification factors, a rotordynamics study may be used to establish seal clearances throughout the compressor, based upon the predicted operating mode shape. Of course, this design option can be incorporated in any seal upgrade project, if a recent rotordynamics study was performed or if one is performed in conjunction with the project.

Lastly a short discussion on teeth-on-stator (TOS) vs teeth-on-rotor (TOR) seals is in order. It has been found that TOS seals are superior to TOR seals from a stability viewpoint (11,12). This should be considered if an option of converting to a TOR system is evaluated (unless a honeycomb seal is used).

CHEMICAL COMPATIBILITY

As mentioned earlier, the compatibility of the thermoplastic with the process (or anything else it may come into contact with) is a very important topic. Parts have been known to dissolve completely into the process, when this area was not properly considered. However, since the compatibility of a given thermoplastic to the application depends specifically on the process and the thermoplastic, a thorough discussion cannot be presented here. It is important to understand that a potential problem does exist, and an analysis of the total process against the thermoplastic is always required. Factors that effect this include the chem-

ical makeup, temperature, pressure, concentration, and time duration. Any chemical the seal may see (such as solvents and wash oils) should be evaluated. If necessary, a precision coupon sample of the polymer under consideration should be put into the process stream for a period of time. The sample can then be evaluated for any degradation.

It is also interesting to note that there have been instances where a thermoplastic part was supplied to combat a chemical attack problem. A photograph is presented in Figure 10 of an aluminum seal that was being attacked by the process. The compressor was opened up at every available outage just to replace the seals. The seals were then remade from a polymer; now they have more than tripled the time between overhauls. (An online wash system helps reduce the total number of compressor overhauls.)

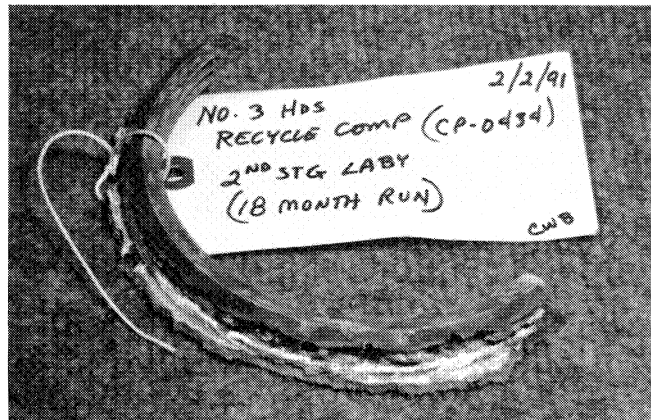


Figure 10. Aluminum Labyrinth Seal Attacked by the Process.

Another aluminum seal that was being attacked by the process is shown in Figure 11. This particular compressor has levels of sulfuric acid that even attacks the polymer (PEEK, in this case) at elevated temperatures. The cooler stages have been upgraded however thereby increasing the overall reliability of the compressor. This upgrade has increased the time between overhauls and also helps the compressor maintain efficiencies.

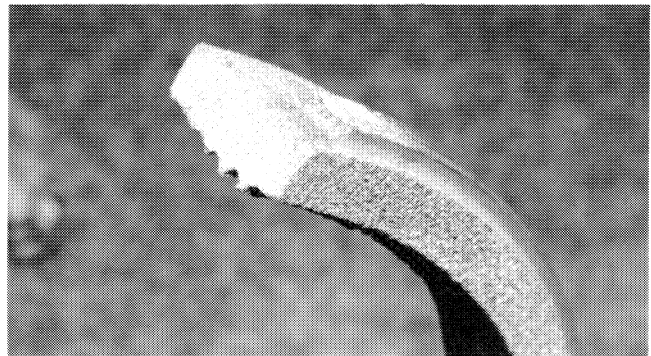


Figure 11. Aluminum Labyrinth Seal Attacked by the Process.

PROBLEM INSTALLATIONS

To the best of the authors knowledge thermoplastic labyrinths were first applied in an industrial centrifugal compressor in July 1988. That machine, an FCCU wet gas compressor, is still running today with PAI in it. The applications remained sparse

until 1990-1991. Since then, the applications have been growing steadily.

These applications are relatively new and some problems have been encountered. The next few sections will address some specific PAI failures. Understanding these failure mechanisms will help assure they will not be repeated.

Chemical Incompatibility

This failure involved a two stage high pressure (HP) syngas compressor in an ammonia plant. The syngas was analyzed and was found to be compatible with the PAI. However, it was not discovered until after a seal disintegrated that hot ammonia was being injected in the recycle stream into the second stage of compression. The first eye seal in this second stage, which saw the brunt of the ammonia, was attacked and dissolved.

This should help to reinforce the concept of fully evaluating all process constituents prior to an upgrade. The low pressure compressor and the first stage of the HP compressor were not damaged.

Improper Installation

The seal portrayed in Figure 12 failed due to high vibration caused by a severe rub on all the labyrinths in the machine. This seal is from a barrel compressor in CO₂ service that started up with the rotor sitting on the labyrinths. The PAI seals were tighter than the aluminum seals being replaced, they were designed to have clearance to the shaft. The rotor was measured and the seal bores were measured in their diaphragms. Comparing these values confirmed that the seals should have had adequate clearance. However, this did not account for the fact that the rotor was not concentric to the seals.

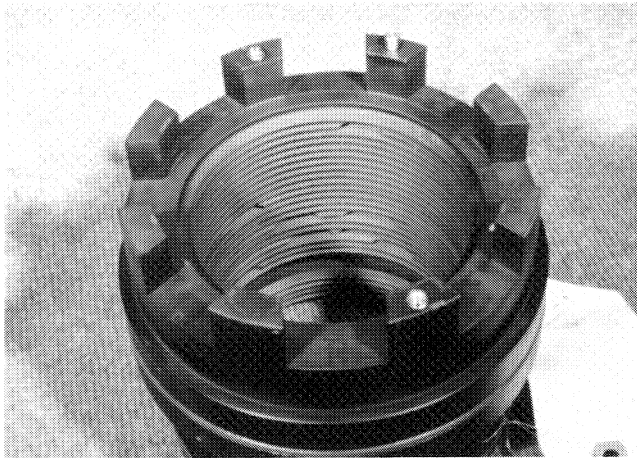


Figure 12. PAI Seal Failure Attributed to High Vibration Caused by Rub Due to Inadequate Polymer Seal Clearance.

Since it is a barrel machine, it was not possible to verify adequately that the seals had clearance all around at startup. Normally, if a seal is rubbing hard, it would be noticed when the rotor is turned by hand. In this instance, the rotor turned free, even though the PAI was apparently rubbing on most, if not all, of the seal locations throughout the machine. This is attributed to the flexibility of the teeth, the light rotor, and the low coefficient of friction of the PAI on the steel shaft.

It is important during installation to do whatever is possible to ensure that the seals have clearance on all sides prior to startup. This is usually easy to do on horizontally split machines where it is possible to get access to the seals while the rotor is in place.

For barrel compressors, it may be possible to do a lift type check with the rotor in the bundle to verify clearances. Be aware at this point that the teeth may defect some giving erroneous readings. The lift checks should agree fairly closely with the measured readings. Then with the rotor and bundle in the compressor repeat this check. Finally put the bearing brackets on and repeat the check. Deviations may be attributed to seal interference.

Starting up on the seals excited the rotor, causing high vibrations; meanwhile, the seals heated up, growing into the shaft, further compounding the problem. An attempt to bring the machine up in speed resulted in very high vibration levels that severely damaged most of the seals.

It should be noted that this type of failure occurred on similar trains (CO₂ barrel compressors manufactured by the same OEM) at two different facilities. The two sets of PAI seals were made by two different suppliers ruling out a specific design or manufacture problem with one supplier. As noted later, one of the most successful case histories involves a horizontally split CO₂ compressor in a third ammonia plant.

Since it is impossible, with barrel compressors, to absolutely verify that there is clearance between the seals and the rotor at installation, it is the author's opinion that larger than standard polymer seal clearances should be used to help avoid this type of problem.

Improper Startup

A seal that was damaged on startup is portrayed in Figure 13. This was a smooth bore balance piston seal; the grooves in it are from the teeth on the balance drum. The startup procedure was modified to take extra care of the newly installed PAI seals. An additional hold point was added to the procedure that happened to coincide with the critical speed of the compressor in question.

The high vibration levels caused a hard rub of the rotating teeth into the smooth bore PAI. The friction generated caused high localized heat buildup, which caused the seal to grow further into the drum, compounding the problem. The PAI is a very poor heat conductor; thereby keeping all the heat localized where it would do the most damage. The flat lands in the bore of the seal in Figure 13 were formed by the flat roots between the teeth on the drum, illustrating the extent of the seal damage (the drum was undamaged).

It is important to take extra care during startup without adding any extra problem areas. As will be shown in the next case, this seal was already very susceptible to a failure of this type. All the other seals in the compressor came through this startup unscathed and they are still running in the machine today.

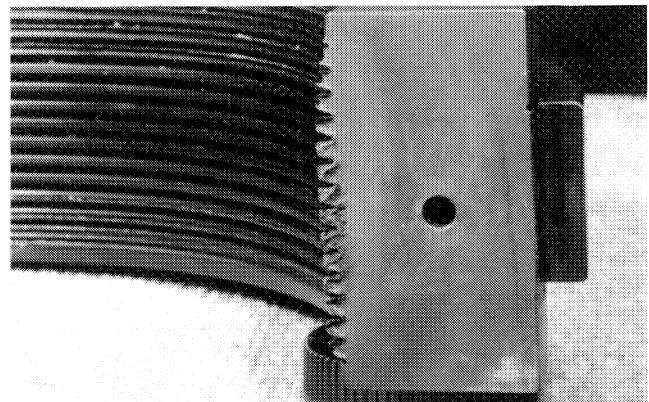


Figure 13. Failed Polymer Balance Piston Seal. Lack of abrasibility with smooth bore polymer seal, coupled with high vibration from critical speed, caused failure.

Improper Design

The seal shown in Figure 14 failed after several months in service and after a few process upsets. This seal is from an LP air compressor. A closeup is shown in Figure 15 of the split line of this seal. This seal was originally a smooth bore seal, sealing against rotating teeth on the balance drum. A rub during a process upset caused heat buildup that closed up the seal bore. This happened over a long enough period of time, so that when the upset was over, the seal had already grown into the drum and the failure was in process. The high heat generated, combined with the air flow across the seal, caused the damage as shown.

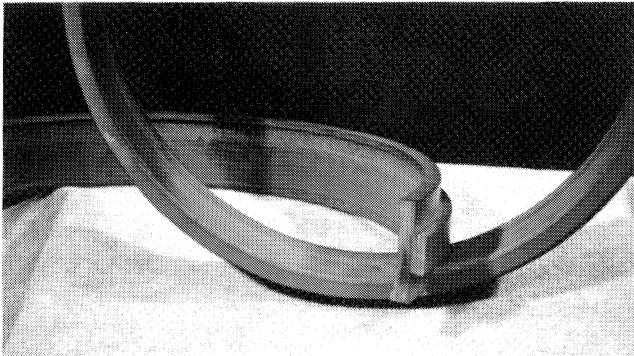


Figure 14. Failed Polymer Balance Piston Seal. Lack of abrasability with smooth bore polymer seal, coupled with vibration excursion from process upset, caused failure.

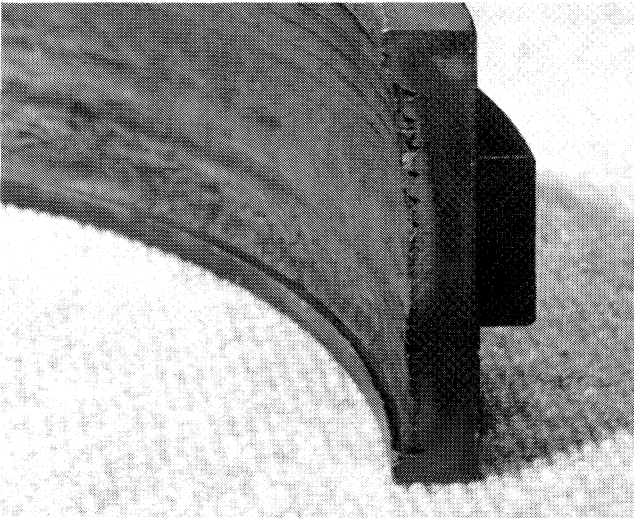


Figure 15. Closeup of Split Line of Seal in Figure 14.

Thermoplastics do not have the abrasability required for smooth bore applications. Some of the more common materials used in smooth bore applications are listed in Table 2. If there are problems with a specific material, another may be used in its place. For instance, if surges cause the babbitt or lead to melt out, then the nickel graphite material would be a logical upgrade.

Stress Failure

Photos are presented in Figures 16 and 17 of a seal that failed in service. The break initiated in the highest stressed area of the part, in a point of stress concentration. The part did not have a proper radius to reduce the stress concentration effects. As such,

Table 2. Smooth Bore Seal Material Options.

1. Babbitt
 - ▶ Low application temperature
2. Lead
 - ▶ Higher application temperature (still low)
3. Mica filled TFE
 - ▶ Higher application temperature (to 350 deg F)
 - ▶ Very weak material (1000-1200 psi tensile)
 - ▶ usually needs to be installed in metal holder
4. Feltmetal
 - ▶ Long lead time
5. Honeycomb
 - ▶ Excellent rotordynamic properties
 - ▶ Long lead time
6. Nickle Graphite
 - ▶ High temperature (900 deg F continuous use)
 - ▶ Short lead times

since the PAI is brittle, a crack initiated that led to the failure. The downstream portion lodged into the holder, while the remaining portion of the seal (with the hook) still did some sealing. High thrust bearing temperatures indicated a potential balance piston seal problem. There was enough time to bring the train down in a controlled manner, so the seal could be replaced. All the other PAI seals in the machine were in excellent condition and are running today.

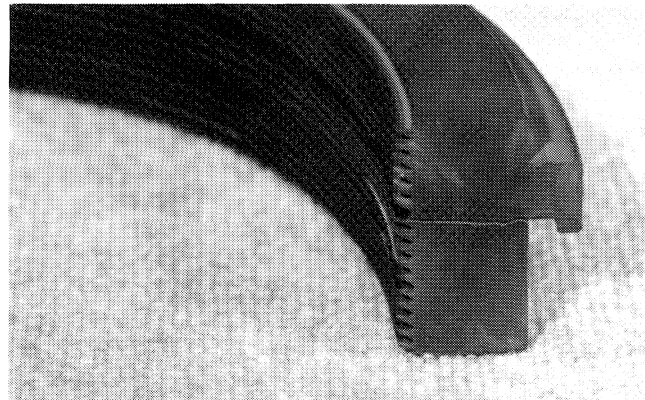


Figure 16. Failed Polymer Balance Piston Seal. Stress risers in corner of hook fit area initiated seal failure after a process upset. Seal lacked proper radii to reduce stress concentration effects.

In all of these instances, the shafting was not damaged by the PAI. There had been instances where a similar upset with aluminum seals had caused severe galling of the rotor in the seal area. With the PAI, a black residue was present on the shaft that could be easily removed.

SUCCESSFUL APPLICATIONS

Of course, there have been many successful applications of these materials. As a matter of fact, most of the machines discussed above are still running with several PAI seals, and are considered to be successful installations. At this time, no installation has been instrumented thoroughly enough to document exactly the efficiency improvements obtained. A few cases will be presented to document the success of the installations.

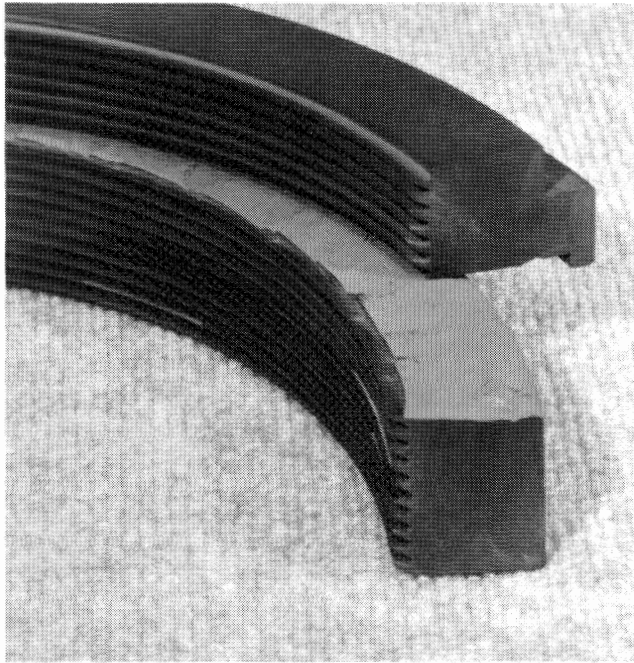


Figure 17. Another View of Seal in Figure 16.

Air Compressor in an Ammonia Plant

A dropoff in performance over time has always occurred with this train that consists of a LP horizontally split case and an HP barrel compressor. Upon installation of the PAI seals, this dropoff did not occur. As such, the performance of the upgrade was sufficient to allow justification for the plant to proceed with the procurement of a set of seals for a sister machine and a set for common spares.

Refinery Wet Gas Compressor

Even though actual dollars saved by increased production are not available, it is known that the payback was very short. A set of spare seals was put on order shortly after process personnel evaluated the performance gains.

Air Compressors in a Chemical Plant

This three body train is driven by an electric motor. All three bodies were upgraded with PAI seals. Upon startup, operations confirmed that more air was available than ever before. Also, the motor was drawing two percent less amperage.

Some of the seals used in this upgrade are shown in Figure 18. Note the end case seals are designed with the thermoplastic inserted into an aluminum holder.

Air Compressors in an Ammonia Plant

The air train in this plant was a bottleneck. The upgrade to PAI seals moved the bottleneck from the air train to a boiler feed pump, while still allowing the train to run several hundred rpm slower, thus offering steam savings.

Air Compressors in an Ammonia Plant

Since the upgrade to PAI seals, this plant has been regularly setting production records. Operations personnel confirm that the increased amount of available air is the major factor in the increased production. It has been reported that there has been a seven to ten percent efficiency gain in the compressor train.



Figure 18. Typical Set of PAI Seals.

Ammonia Plant CO₂ Compressor

The compressor in this single body train, driven by an electric motor, has a horizontally split case, and two stages of compression with five wheels per stage. Process people at this plant calculated a 12.2 percent increase in throughput after a PAI upgrade. All of the seals used in this upgrade are shown in Figure 19. This is the machine that experienced a balance piston seal failure. After the OEM balance piston seal was installed, the efficiency dropped about six percent (a six to seven percent efficiency gain was still realized).

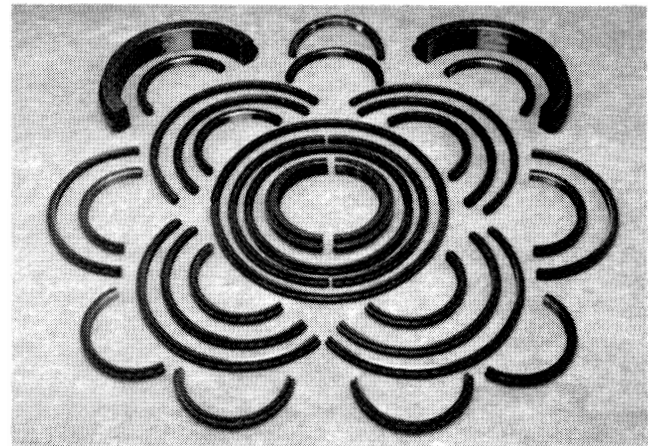


Figure 19. Set of PAI Seals for CO₂ Compressor. Note that the balance piston seal subsequently failed (Figures 16 and 17).

Ammonia Plant LP Air Compressor

After conversion of all seals from aluminum to PAI a 5.6 percent gain in compressor efficiency was reported. Even though these case histories are not thoroughly documented the benefit in the application is clear. Taking all of these case histories into consideration it has been found that a one-half to one percent per wheel increase in compressor efficiency can be expected. Hopefully, in the near future, a compressor will be adequately instrumented, so efficiency increases can be completely and formally documented.

CONCLUSIONS

With proper considerations, thermoplastics can be successfully applied to centrifugal compressor labyrinths. A plant considering an upgrade of this type will hopefully find this information useful in evaluating the materials and applications.

Basically, a successful installation will involve:

- Total process compatibility evaluation.
- Thermal expansion calculations.
- Stress Analysis.
- Proper seal design and application (learn from past failures).
- Careful seal installation.
- Careful machine startup.

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