Silicone vs. TPE: How to make the right choice

Choosing the right TPE: The seven essential considerations

High heat copolyester elastomers for rubber replacement

Styrenic block copolymers for copolyester modification

Perspective: Evolution is key to success of revolutionary Santoprene thermoplastic vulcanizate
High heat copolyester elastomers for rubber replacement

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One of the strategies automotive OEMs are utilizing to meet future CAFE requirements is the deployment of turbocharged engine configurations on a broader scale in consumer market light vehicles. Turbocharging with charged air coolers (CACs) is one of the most cost-effective options vehicle manufacturers have today to increase engine efficiencies. With turbocharging, the engine aspirates the same volume of air during the intake stroke of the piston, but since the air is pre-compressed, a greater amount of oxygen is available and more gasoline can be burned during the combustion cycle. This increases power generated per combustion cycle. By designing new engines with fewer cylinders, power output on turbocharged vehicles can be maintained, while fuel consumption and vehicle emissions decrease.

Compressing the air in the turbo creates friction heat between air molecules, typically about 175°C. The hot charged duct (HCD) is used to transfer the compressed air from the turbocharger to the CAC in both gasoline and diesel fuel engines. Current state-of-the-art for an HCD is a multi-layer fabric reinforcement, typically woven from a polyaramid fiber. Wall formulations in different layers. Because of the heat, the fabric reinforcement is typically woven from a polyaramid fiber. Wall thickness for the full laminate structure is between 5 to 6 mm. The plastic may be supported with stainless steel metal rings at each end or the clamps to the rubber hose to mitigate the risk of creep failure and any associated air leakage at the assembly joint. The final HCD is based on up to seven or nine highly engineered and tooled components, made from different materials, in several different processes that must be assembled together.

One end of this expensive and complex assembly is clamped to a turbo outlet or resonator on the engine and will move with the engine, and the other to a chassis mounted CAC that is fixed in place. The HCD must have sufficient flexibility at cold temperatures in order to mitigate the loads that are transmitted to mating components as a function of engine roll. At high temperatures, the HCD must withstand the mechanical loads and internal pressures under all operating conditions, creating one of the most demanding duct applications on a vehicle. The weight, complexity and cost of these HCDs per unit of length is high relative to ducts elsewhere on the vehicle.

The new high temperature TPC (HT TPC) dramatically simplifies the HCD assembly. Instead of up to nine discreet pieces, the HT TPC uses only three; the duct itself and two end fittings. This clearly leads to fewer parts that must be engineered and tooled and manufactured and assembled.

The thermoplastic copolyester solution: Reducing complexity

DSM Engineering Plastics is a market leader in air intake manifolds, with a portfolio of nylon materials for conventionally aspirated engines. DSM also supplies materials for every component in the turbocharged air induction loop that can be manufactured from thermoplastics. DSM’s portfolio of applications includes resonators, ducts, CAC end tanks, throttle bodies, waste gate valve housings, elbows, end fittings, brackets, etc. For HCDs, glass reinforced nylon 46, nylon 66 and nylon 6 have traditionally been supplied as the structural component in the assembly to which rubber cuffs are clamped. Materials supplied include injection molding grades for ducts, or blow molding grades for ducts, depending on the design preferences for a given engine or vehicle platform.

TPCs have been in the market since the 1970s. The traditional TPC materials are polyether-based and compete against rubber capable of functioning at lower temperature regimes (figure 1). Typically, these types of polyether ester elastomer chemistries are cost and performance competitive with materials like epichlorohydrin rubber or nitrile rubber. They are manufactured in condensation polymerization processes from a polyester and a diol as block copolymers. DSM manufactures materials from 25 durometer D with a stiffness of 25 KPa, to 74 durometer D with a stiffness of 900 KPa. DSM has a global leadership position in TPCs, and markets TPC under the tradename Arnitel.

There are many automotive applications utilizing TPCs, from interior components to under-hood parts like constant velocity joint (CVJ) boots and propshaft boots, wire and cable primary insulation and tubing applications. “Traditional” lower temperature applications where polyether based TPCs have been used for many years also include cold charged ducts (CCDs) that handle air flow from the CAC to the throttle body. In this case, the air temperature inside the duct is the outlet air temperature after the CAC, and is typically ~80°C. TPCs can also be used in clean ducts after the filter and before the cold side air intake of the turbo charger. In every case, these materials are limited to continuous use temperatures (CUTs) of up to ~125°C. CUT is defined, in
requires considerable process development and upgrades to the polymerization process in order to manufacture the material at the level of consistency mandated by the market.

When converting a part from rubber to a TPC, the strengths and weaknesses of the different classes of materials must be taken into account. Rubber is excellent in deformation characterized by motion associated with hysteresis, while TPC is not. TPC is excellent in deformation characterized by motion associated with flex fatigue, while rubber is not. Consequently, when switching a duct from a high heat rubber to an HT TPC, the part needs to be redesigned to leverage the strengths and mitigate the weaknesses of the substitute material. A rubber to TPC redesign usually entails:

1. Reduce the wall thickness by 1/2 to 1/6 the thickness of the original rubber part.
2. Leverage the flex fatigue capability of the TPC by designing in enough “hinge” points to effectively use the capability of the TPC.

**Vision for success**

In the most basic sense, the function of an HCD is to reliably deliver pressurized air from the turbo charger to a CAC with minimal pressure drop. The vision of an HT TPC HCD is to deliver this function, along with system cost reduction, mass reduction, reduced complexity and the elimination of potential leak points inherent in the state-of-the-art rubber duct assembly. Figure 3 shows a schematic of a complex rubber duct assembly and a simplified HT TPC duct design.

Figure 2 - simplified Arrhenius plot comparing traditional polyether based TPCs to the new HT TPC capable of competing with acrylic rubber and silicone rubber

![Figure 2 - simplified Arrhenius plot](image)

with acrylic rubber and silicone rubber.

Temperature (°C)

Plot based on 100% strain at break retention value

• Arnitel HT8027
• Traditional polyether-based TPC

Time (hours)

0 50 100 1,000 10,000

250 200 150 100 50 0

100°C 150°C 200°C 250°C

This case, as reaching the selected end point criteria after 3,000 hours in an Arrhenius plot.

With respect to Arrhenius plots, defining the key mechanical properties needed to assess in conjunction with thermal aging is a critical first step. In this regard, attention is turned to the tensile elongation of the material. Tensile elongation is a key mechanical property associated with both duct compliancy, as well as burst pressure resistance. Retaining ample elongation at break helps ensure that a duct does not crack at cold temperatures, nor prematurely burst at high temperatures.

The new HT TPC has a CUT of 175°C, defined using the same end point criteria as traditional polyether based TPCs. This is a huge increase in capability for TPCs; approximately 50°C (figure 2).

The simplified Arrhenius plot deserves additional discussion.

In this case, the HT TPC Arnitel HT 8027 is compared against a control, a traditional polyether-based TPC. The oxidative aging behavior of this product can be considered among the “best in class for traditional TPCs.” The end point criteria for this plot are an absolute elongation at break of 100% in a tensile test per ISO 527-1/-2. If the OEM defines CUT as 1,000 hours, the Arnitel HT 8027 is capable of a CUT of 192°C, whereas the traditional TPC used as a control would be capable of 148°C. As an initial estimate, the Arnitel HT8027 is an improvement of 44°C. If the customer defines CUT as 3,000 hours, the Arnitel HT 8027 is capable of a CUT of 175°C, whereas the control would only be capable of 127°C. The difference in capability is now 48°C. These observations are based on the end point criteria of 100% absolute elongation at break. If an OEM has a different preference for end point criteria, the curve will shift accordingly.

The automotive industry has been utilizing the capability of HT TPCs since the mid-90s for other applications. The most broadly adopted use is headlight wiring applications where Class D rated wire (CUT of 150°C to 175°C) is required as a part of the lighting system. The use of HT TPC as the primary wire insulation has been globally accepted for over 20 years by OEMs in every region of the world. DSM’s key innovation takes the HT TPC that is readily accepted by the industry for uses under the hood, and adapts the material to make it suitable for use in the 3D suction blow molding duct manufacturing process. The effort
To deliver this vision, the HT TPC must meet the performance requirements of an HCD. As described previously, the demands from pressure, temperature, environment and induced stress all need to be considered in validating a material for this demanding application. To meet these requirements, the associated development efforts are focused on meeting two fundamental assessment criteria:

1. Mechanical property retention after long-term thermal aging that captures the effects of thermal load anticipated for the material through its service life: material based.
2. Pressure, movement and temperature bench test, which is designed to capture the rigorous performance requirements of an HCD throughout its service life: part based.

While there are also HCD performance requirements specific to chemical resistance, as well as acoustic performance, aspects of these requirements are not presently covered in this study.

Material based heat aging performance
As acknowledged previously, tensile elongation is identified as the critical material property in defining CUT. Measuring this material property in a fashion that is most appropriate for a blow molded duct merits attention in regard to sample preparation. In the case of injection molded ISO test specimens, it has long been acknowledged that the mechanical property of a TPC material is influenced by the molecular orientation induced by the high pressure injection molding process. Because molecular orientation plays a part, attention must be paid to whether tensile testing of HT TPC is based on “in process flow direction,” or a die-cut specimen “normal to process flow direction.” The stress strain curve associated with each approach is distinct, and a rationale to pursue one or the other in the context of the blow molded duct program is merited.

To assess which orientation is most appropriate for representing the performance of a blow molded HCD, a study was conducted in order to compare the stress strain curve of a specimen extracted from a low pressure, blow molded part to the stress strain curve of specimens extracted from the “in process flow direction” and “normal to process flow direction” of a high pressure, injection molded specimen.

The comparative stress strain curves are shown in figure 4. The results indicate that the use of die-cut specimens “normal to process flow direction” is, in fact, a good proxy for the anticipated stress strain performance of the low pressure, blow molding process. Furthermore, the shape of the curve associated with the die-cut specimen “normal to the process flow direction” emulates the shape of the stress strain curve, which is extracted in the “hoop” direction of the blow molded part. This proves to be critical, as far as the stresses in the hoop direction typically dictate the burst pressure performance of a tubular duct.

Accordingly, the data generated for the previously discussed Arrhenius plot are based on test specimens die cut from injection molded plaques perpendicular to flow. As previously acknowledged, the Arrhenius plot indicates HT TPC property retention performance that is suitable for the anticipated temperatures associated with a turbo-charged gasoline engine HCD.

Part based performance
With the foundation of robust HT TPC heat aging performance, attention is now turned to the aspects of pressure, movement and temperature from a part design perspective. The duct needs to fulfill performance requirements at both the low temperature extreme, as well as the high temperature extreme. Acknowledging this, a starting design approach is established as follows:

1. Establish the minimum nominal part thickness that delivers sufficient high temperature burst pressure resistance.
2. Confirm the ability of the part to withstand pressure pulsation at this minimum nominal thickness.
3. Confirm that low temperature load transmittal to the connection end fittings at this minimum nominal thickness is acceptable.

While the approach outlined above represents a simplification in addressing the complex performance requirements of an HCD, the basis is sound and merits an acknowledgement of the
temperature, as well as aspects of material rigidity at cold temperatures. Dynamic mechanical thermal analysis (DMTA) plots provide insight into both the material’s ability to withstand short term mechanical demands at high temperature, as well as aspects of material rigidity at cold temperature. Figure 5 shows the DMTA comparison for TPC and HT TPC materials. In reviewing the DMTA plot, consider that TPC materials have traditionally been positioned for cold charged ducts that achieve peak temperatures of ~125°C. For HCD applications, the requirements for HT TPC are pushed to the right of the plot and towards peak temperatures as high as ~190°C. In considering this incremental temperature delta of ~65°C, be mindful of the corresponding drop in mechanical properties, as displayed in the DMTA plot.

With peak temperature performances in mind, the focus is first on high temperature burst pressure performance. In establishing the minimum nominal part thickness for burst pressure resistance at high temperature, thin wall pressure vessel calculations are considered. While this approach does not adequately capture the part specific nuances of a complex, blow molded part, it does provide a starting point for targeting what may be considered a minimum wall thickness. With this approach, the duct diameter, temperature and pressure values of interest need to be established. Figure 6 shows an example based on a 4.2 bar burst pressure requirement. In applying this approach in practice, a minimum duct thickness is established as a starting point.

Establishing a minimum wall thickness based on high temperature performance also serves to minimize the rigidity of the duct. As shown on the DMTA plot, the TPC and the HT TPC materials’ modulus “E’” increases as the temperature gets colder. Part rigidity is a function of both material modulus “E,’” as well as sectional modulus “I.” Establishing the minimum HT TPC duct thickness reduces “I,” which in turn helps to compensate for increasing “E.” This ultimately mitigates load transmission, which can be crucial at cold temperatures. Equally compelling, of course, is the fact that minimizing wall thickness helps to deliver the vision of cost reduction and mass reduction as compared to the rubber duct assembly. Table 1 displays how nominal thickness for a given cross-section impacts both mass (based on cross-sectional area), as well as load transmission (based on sectional modulus “I’”).

Aspects of duct length, cross-sectional variation, thickness variation along the length, as well as the number and angle of bends, all influence the load transmitting nature of a duct. As a sole factor, sectional modulus “I” is not suitable for defining the load transmitting nature of a given duct, but it does provide a directional indication of how duct compliancy may be favorably impacted by thickness reduction for a given material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cross-section</th>
<th>Thickness (mm)</th>
<th>Sectional modulus (x1,000 mm²)</th>
<th>Area (mm²)</th>
<th>Mass per length (g/mm)</th>
<th>Mass reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEM rubber</td>
<td>5</td>
<td>390</td>
<td>910</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HT TPC</td>
<td>3</td>
<td>260</td>
<td>570</td>
<td>0.7</td>
<td>39%</td>
<td></td>
</tr>
<tr>
<td>HT TPC</td>
<td>2</td>
<td>180</td>
<td>385</td>
<td>0.5</td>
<td>59%</td>
<td></td>
</tr>
</tbody>
</table>

Part validation

With the approach outlined above, the HT TPC material has shown to pass OEM test requirements associated with pressure, movement and temperature cycling. This testing incorporates not only internal pressure pulsation and forced duct movement in the x, y, z directions, but also cycles the duct through temperatures below -30°C and up to the anticipated operating temperatures in the range captured by the previously discussed Arrhenius plot. In these cases, industry standard quick connect end fittings have been employed. For part rigidity, it is noteworthy that...
HT TPC ducts that have successfully passed the OEM testing span a length/diameter ratio of 15:1 to 10:1 when considering the length between fixation points.

System cost reduction
As acknowledged previously, the vision for the development and validation of HT TPC in HCDs is to achieve a lower system cost, reduced part mass and reduced leak path alternative to the state-of-the-art rubber duct assembly that is in use today. In order to properly understand the vision of system cost reduction, DSM worked with an outside consultant in order to establish a cost model which aids in comparing the cost between an HT TPC duct solution and the rubber duct assembly, which is in use today.

The cost model allows for adjustment of many input parameters, including thickness, duct length, overhead and throughput rates. The cost model, as validated by part suppliers on more than one occasion, indicates that the HT TPC solution can offer compelling system cost reduction compared to the incumbent rubber duct assembly used today. In some cases, the modeled cost comparison indicates as much as a 32% reduction in system cost for the HT TPC solution. An example of the cost model output is shown in figure 7.

Conclusion
In conclusion, the HT TPC duct solution delivers:
- Excellent property retention at CPT up to 175°C and peak temperature capability up to 190°C
- Flexibility and ductility at low temperature
- High temperature properties that enable thinner walls and up to 50% mass reduction versus rubber
- Fewer potential leak paths
- System cost reduction

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