Abstract
Sensors and actuators used in the engine compartment are being exposed to higher temperatures, more aggressive media and more extreme thermo-mechanical loads than ever before. These combined stresses are imposing requirements that increasingly exceed the capabilities of the polymers traditionally used to encapsulate and mount electronic components. In such cases, switching to engineering polymers that offer higher performance can provide a cost-effective solution.

High-performance polyamides and optimized thermoplastic polyesters, in particular, have the required performance reserves. With reference to selected examples of underhood applications, innovative solutions are highlighted and pointers to the future discussed.
Wide-ranging potential for polyamides and thermoplastic polyesters

Underhood applications are traditionally an area for semi-crystalline engineering thermoplastics, specifically polyamides of the PA66 type and thermoplastic polyesters, which DuPont sells under the trade names Zytel® and Minlon® (nylon resins) and Crastin® (polybutylene terephthalate, PBT). Polymers that offer even higher performance, such as semi-aromatic polyamides (e.g. Zytel® HTN), Rynite ® (polyethylene terephthalate, PET) and Thermx® polycyclohexylene dimethyl terephthalate, PCT) are attracting increasing interest today.

Semi-aromatic polyamides withstand heat, chemicals and moisture

The main advantages of semi-aromatic polyamides over the classic PA66 grades lie in their higher resistance to moisture, high temperatures and media typically encountered in the engine compartment, such as fuels and lubricants. Semi-aromatic polyamides have a much lower tendency to thermooxidative degradation and offer an overall improvement in dimensional stability (Fig. 3).

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The special properties of semi-aromatic polyamides are determined by the aromatic monomers used in the polymerization process, such as isophthalic acid or terephthalic acid, and the choice of the aliphatic component in copolymerization, e.g. PA66. In addition, the property parameters can be further influenced by blending with other polymers. The larger the aromatic component (e.g. PA6T) is in such materials relative to the aliphatic PA66, the higher the resulting glass transition temperature and the lower the undesirable water absorption. In DuPont’s product portfolio, the grade Zytel® HTN 51 receives top marks on both counts (Fig. 4).
Optimum requirements for low-stress processing

Above and beyond the need for wide-ranging resistance, sensors and actuators also make special demands on the processing behavior of a material during encapsulation. Among the critical factors are:

- The shrinkage behavior of the plastic and the resulting internal stresses
- Flowability, which determines the required pressure in overmolding
- Dimensional stability, which decides the thermo-mechanical stress to which the electronic component is subjected in the event of temperature changes
- Weld line quality
- The strength of the material’s adhesive bond to itself and to other thermoplastics used to encapsulate the same component
- Resistance to cyclic temperature stress, which is co-determined by weld line strength.

The Zytel® HTN grades from DuPont score very well on all counts but differ between themselves in relation to their specific formulation to meet certain key requirements of individual applications.

In Fig. 5, the shrinkage values of a typical PA66 grade (Zytel® 70G35HSL, 35% w/w GF, heat-stabilized, lubricated) are shown alongside those of two comparable high-performance polyamides with the same glass fiber content (Zytel® HTN 53G35HSLR and 54G35HSLR). The clear superiority of the HTN grades is consistently apparent, whether freshly molded or annealed, and irrespective of the selected injection molding parameters. The differences compared with the PA66 tested are in the region of 30%. This means that the cooling process is correspondingly more gentle when the sensor and actuator components have been encapsulated with these semi-aromatic polyamides.

Processors can exploit these shrinkage advantages without compromising the mold filling capacity of the Zytel® HTN grades. Fig. 6 compares the results of flowability measurements in the spiral flow test. The results for the lower wall thickness of 1 mm are more strongly influenced by the crystallization rate of the material, while the data for 2 mm wall thickness tend to be indicative of the material’s melt viscosity. Both the grades Zytel® HTN53G35HSLR and HTN51G35HSL attain the familiar good values of the 30% w/w glass-fiber-reinforced comparative material, the PA66 grade Zytel® 70G30HSR2. The corresponding HTN54 and HTN52 grades surpass the comparative material in all cases by around 20%. This makes it possible to reduce the injection pressures used in processing these semi-aromatic polyamides and so prevent unacceptable damage to the electronic components.
Thermal expansion (and dimensional stability generally) is crucial in determining the mechanical stress imposed on encapsulated electronic components due to ambient temperature changes. Such changes are characteristic of the environment in the engine compartment and can range from -40°C for a cold start in winter to over 150°C in the vicinity of the running engine. On account of their significantly higher glass transition temperature, the semi-aromatic polyamides once again have clear advantages in the upper temperature range – similar to their shrinkage advantages in cooling from melt temperature. As Fig. 7 shows, the thermal expansion of Zytel® HTN54G35HSLR at 160°C is only half that of the PA66 comparative grade.

The resistance to cyclic temperature stress of an encapsulated component is primarily determined by the load-bearing capacity of the weld line (where the divided melt streams reunite) and the strength of the adhesive bond between the materials (in overmolding). Weld line quality and adhesive bond strength decide the fluid-tightness of the entire encapsulation and therefore the reliability of the encapsulated electronic components.

To test the adhesive bond, DuPont produced two special test bars, which were injection molded in two successive cycles. In one test bar, the weld was designed with so-called melt ribs, simulating common industrial practice, while, in the other case, the weld took the form of overlaps, which are also frequently used (Fig. 8). With the butt joints in the tensile test, two of the test specimens (Zytel® 70G33 and HTN51G35HSLR) exhibited adhesive failure at high tensile force. The HTN grades 53G50HSLR and 54G35HSLR even displayed the desired cohesive failure, in which the material fails outside the weld, which is a sign of very good adhesion in insert molding/overmolding. In the case of the overlapping, shear-stressed interfaces, all three semi-aromatic polyamides tested showed a significantly better result, withstanding tensile forces up to six times higher than PA66.
To assess the weld lines formed at the point where two melt streams unite, tensile test bars were produced by injection molding in one cycle and gating from each end. They then underwent tensile testing. The results in Fig. 9 show that, although the semi-aromatic polyamides tested did not achieve the familiar good weld line strength of the PA66 grades, the reductions in tensile strength and elongation at break were low, especially with the highly filled Zytel® HTN53 and HTN54 grades.

Semi-aromatic polyamides successfully proven in practice

The excellent property profile of the semi-aromatic polyamides has been confirmed in many successful industrial applications (Fig. 10).

Siemens VDO (A) uses a Zytel® HTN in the 54 series to encapsulate engine speed sensors. The semi-aromatic polyamide offers good mold filling capacity, despite the 35% glass fiber reinforcement, and permits low-stress processing. This results in high resistance to cyclic temperature stress, low creep and low thermal expansion, so ensuring fluid-tight encapsulation. It also allows an economic water-heated mold to be used.

Valeo (B) uses a Zytel® HTN in the 54 series for a solenoid valve in the exhaust gas recirculation system. Here the level of glass fiber reinforcement can be increased, because a more robust metal part is being overmolded. The higher glass fiber content is also required to minimize thermal expansion and the occurrence of thermo-mechanical stresses, and to ensure the necessary rigidity at the high exhaust gas temperatures.

Woco (C) produces the housing and components for a valve block from a Zytel® HTN in the 53 series, so ensuring low material shrinkage, high dimensional stability, low warpage, retention of mechanical properties and fluid-tight encapsulation, despite the high ambient temperatures.

PA612 for ‘soft-fill’ requirements

The polyamide grade Zytel® 612 is specially formulated to minimize the stress on electronic components during encapsulation and is a standard material for encapsulating sensitive sensors. Its specific advantage lies in its extremely low water absorption of 0.16% (GF33, 24 h immersion), which is way below that of PA66 (0.7%) and also that of semi-aromatic polyamides. It ensures very high dimensional stability and very good retention of mechanical properties. In addition, this material has very high resistance to chemicals such as the CaCl₂ used as road salt in Asia or aggressive blow-by gases.

Besides high dimensional stability, the exceptionally good mold filling behavior of Zytel® 612 is crucially important. Although its melting point (217°C) is significantly lower than that of PA66 (262°C), its very wide pro-
cessing window allows the melt to be heated up to around 80°C above the melting point. This results in very low viscosity. In addition, the crystallization rate is very low (slower freezing of the melt front) so that, even with glass-fiber-reinforced PA 612 grades, very long flow paths can be achieved in very narrow cavities (Fig. 11). This means either that high-strength parts with extremely thin walls can be produced when space is critical or that exceptionally reliable encapsulations can be obtained with low injection pressure and therefore minimal stresses on the electronic components (i.e. ‘soft fill’).

A current example of a Zytel® PA612 application is the wheel speed sensor shown in Fig. 13. The selection criteria for this material were fluid-tightness after encapsulation, melt flowability, media resistance, dimensional stability, low moisture absorption and resistance to cyclic temperature stress.

‘Wire-friendly’ optimized grades in all Zytel® families

PA grades are described as ‘wire-friendly’ if, during processing and use, they have only minimal effects on electrical and electronic components, i.e. they combine ‘soft-fill’ with other properties. On account of their good flow behavior, such grades exert only low mechanical forces on the insert during encapsulation. Even in the long term, they cause no chemical changes in the metal (corrosion) and – depending on the base material – they can be so dimensionally stable that, even in aggressive chemical environments, they retain their geometry within close tolerances. This prevents internal stresses in the plastic that could damage the electronic components. DuPont offers suitably optimized grades in all Zytel® PA families (Fig. 14).

Hydrolysis-stabilized PBT withstands moisture

Where moisture effects are serious and extremely high dimensional stability is required – for example in the encapsulation of sensors and actuators mounted in the close confines of the engine compartment – hydrolysis-stabilized, glass-fiber-reinforced polybutylene terephthalate (PBT) can offer a solution. Crastin® PBT HR from DuPont is a material that meets these requirements, combining exceptional resistance to hydrolysis (compared with standard PBT) with high flowability (Figs 15, 16). In-house tests carried out by DuPont on special test specimens also showed that the resistance of hydrolysis-stabilized Crastin® to cyclic temperature stress (number of cycles to appearance of the first cracks) is three times higher than that of the corresponding standard grade (Fig. 17). Fig. 18 shows a typical application of this material – a housing part for a sensor found in the front headlights.
Suitable for laser welding

Modern joining methods can achieve a permanent reduction in manufacturing costs. At the present time, laser transmission welding is being increasingly used in the production of electrical and electronic underhood components. It is a highly automated and therefore cost-effective assembly method with fast cycles. In addition, it offers the possibility of producing hermetically sealed joints in a very narrowly limited, exactly defined space without subjecting the environment (i.e. the electronic components being encapsulated) to either thermal or mechanical stresses, such as occur with conventional welding methods. The resulting welds are ‘clean’, i.e. with no weld bead or flash, and the quality of the welds can be checked very easily (in-line) by monitoring the welding operation. The high-performance plastics Zytel® HTN, Zytel® PA612 and Crastin® PBT from DuPont are generally very suitable for laser welding, although the actually attainable mechanical strength of the weld depends on the particular material pairing (Fig. 19).

A practical application for laser transmission welding that has proved successful a million times over is this electropneumatic transducer from Pierburg, in which the...
cover is produced from a laser-transparent Zytel® PA66 and the coil bobbin from a laser-absorbing grade of the same material (Fig. 20). To distinguish between specific applications, the individual parts are colored in different combinations.

**Partnership increases competence**

The interrelationships between the functioning of highly sensitive electronic components, such as sensors and actuators, the type of encapsulation and the encapsulating materials used are extremely complex. The decision to use a certain thermoplastic is therefore too much for either the manufacturer or the raw material producer alone. Only the cooperation of both in partnership, and the inclusion of the processor, provide the necessary competence for successful new and further developments.

DuPont brings to such cooperative projects its wide experience in the use of high-performance plastics in the automotive and electrical/electronics industry, as well as the extensive technological resources of a science-based company. These include the production and testing of special test specimens for two-component technology and encapsulation (Fig. 21), the development and validation of specific material pairings for laser welding in close cooperation with an experienced equipment manufacturer, and access to computer capacities and the latest software for component design and stress simulation with the aid of CA technologies. The earlier such cross-disciplinary cooperation begins, the shorter the route can be from the initial idea to commercialization.

![Fig. 21 Special test methods for materials used to encapsulate sensors and actuators](image-url)
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