ARTICLE

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STYLIGHT: A NEW GENERATION OF AESTHETIC COMPOSITES BASED ON STYRENIC CO-POLYMERS

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Introduction

Continuous fiber reinforced thermoplastics are gaining growing importance in various industries due to their lightweight potential, high freedom of design and applicability in mass production.

Apart from their exceptional mechanical performance, however, composite thermoplastic parts currently based on semi-crystalline polymer matrices (PA, PP) usually allow only for a limited surface quality. The imprint of the fiber reinforcement due to shrinkage/ warpage of the matrix and "read-through" of the back molded structural ribs are major reasons. Hence, the applications of composite thermoplastics are so far focused on structural parts without particular aesthetical value.

In a project with R&D partners from academia and industry, a new generation of high strength fiber-reinforced composites based on styrenic copolymers was developed.

This project focused on the evaluation of specific styrene copolymers as a lightweight, robust and aesthetic component. It is supported by the research institutes NMF (Neue Materialien Fürth GmbH) as well as NMB (Neue Materialien Bayreuth GmbH), which joined the INEOS Styrolution research network in 2013.

The INEOS Styrolution Research Network is a unique R&D model in the plastics industry going beyond the classical funding of university projects. At the center of this partnership is a project coordinator who evaluates new technologies for the deployment of styrenics. The most promising findings are being followed up in a cross-functional team by researchers from both parties. This approach constantly grows the innovation pipeline.

In a second step of this project, INEOS Styrolution decided to validate the product development and created a prototype mold to evaluate the processing behavior as well as the surface quality which can be achieved with this new material employing different types of surface decoration.

Performance of styrenic copolymers composite in semi-structural applications

The early technical evaluation of such composite thermoplastic sheets showed that specific styrenic copolymers represented promising new candidates as a matrix.

A modified SAN resin was developed and selected to provide a very high flow and hence enable complete impregnation of the continuous fibers being present typically from 45% to 50% volume content. As the sizing of commercially available glass or carbon fibers are not designed for styrenic polymers in particular, modifications were carried out to make the SAN polymer matrix more compatible to the existing fiber sizing.

These measures led to composite sheets based on glass or carbon fiber fabrics featuring an excellent mechanical performance profile (stiffness, strength, impact strength), being on par with today's most advanced (PA6 or PC based) thermoplastic composites in the market place (see Fig. 1; four layers woven glass fabric with 45% GF volume content in dry conditions measured on 2 mm thick test bars).

StyLight * is the brand name of this new generation of the thermoplastic composites from INEOS Styrolution.

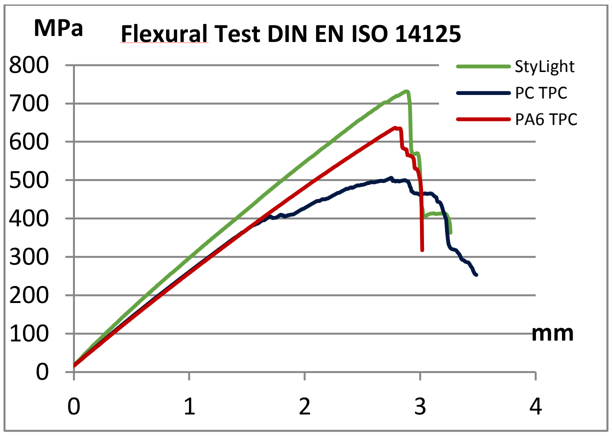

Fig. 1: *Stress deflection curve* ***StyLight**** *vs PA & PC (measured at NMF)*

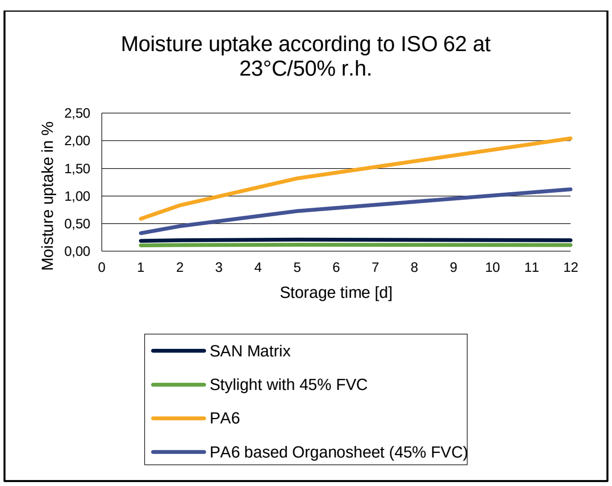

Fig. 2: *Moisture uptake* ***StyLight****vs PA6*

Moreover, the low water absorption (see Fig. 2) of the amorphous styrenic copolymer, combined with its high glass transition temperature of 110C, provides high mechanical stability over a large temperature range. The good stability of styrenic copolymers versus environmental conditions makes this new class of products ideal for technical part design requiring stable properties and dimensions.

StyLight product portfolio

Launched at the Kunststoffe ("K") exhibition in October 2016, ***Stylight**** remains a relatively young material, but INEOS Styrolution already developed and proposes a commercial product portfolio to fulfil the requirements of the targeted applications. This portfolio is divided into two categories, on the one hand products optimized for aesthetic semi-structural applications named "**StyLight** Aesthetic S" and on the other hand products optimised for structural, non-visible applications, called "**StyLight** Structural S".

In this portfolio, INEOS Styrolution proposes products based on Glass woven fabrics, Glass Non-crimp fabrics (NCF) as well as one woven Carbon Fiber grade for aesthetic semi-structural applications. These different textile types offer a diversity of mechanical properties, surface qualities and drapabilities. ***StyLight**** sheets are available in any thickness from 0.25 mm up to 5 mm and in black or natural color. The "Aesthetic S" product range (see Fig. 3) is available with or without a fleece and an extra thermoplastic layer can be applied on demand on the visible side of the application. Until now all these ***StyLight**** products are based on one single type of matrix, i.e. a modified SAN matrix (stands for the "S" in the product name), it is nevertheless not excluded that new styrenic based thermoplastic matrices will be launched in the future to enhance the ***StyLight**** offering depending on market demand.

			StyLight Aesthetic S			StyLight Structural S	
Product name			G290-1*	G615-2*	C200-1	G580-1	G600-3
MATERIAL DESCRIPTION	Standard	Unit					
Fibres			Glass	Glass	Carbon	Glass	Glass
Textile			Fabric: Twill 2/2	Non Crimp Fabric: +/-45°	Fabric: Twill 2/2	Fabric: Twill 2/2	Non Crimp fabric: 0°/90°
Area weight		g/m²	290	615	200	580	600
Yarn		tex	204	300	3k	1200	1200/300
Weight rate		%	50/50	50/50	50/50	50/50	80/20
Polymer			Modified SAN	Modified SAN	Modified SAN	Modified SAN	Modified SAN
Fibre content		vol-%	45	48	45	45	47
Thickness per layer		mm	0.25	0.5	0.25	0.5	0.5
MECHANICAL PROPERTIES							
Tensile Modulus, 23°C	[ISO 527-4]	MPa	23900	24500	53900	22600	32700
Tensile Strength, 23°C	[ISO 527-4]	MPa	490	450	520	450	760
Tensile Elongation, 23°C	[ISO 527-4]	%	2.6	2.4	1.0	2.4	2.5
Flexural Modulus, 23°C	[ISO 527-4]	MPa	25500	34900	45900	27400	37400
Flexural Strength, 23°C	[ISO 527-4]	MPa	720	880	770	590	1100

* exist with or without Fleece

Fig 3: StyLight* *sheet product portfolio*

The thermoformed composite sheet is in most cases only one component of the application, a back injection molded reinforcement is typically needed for three-dimensional parts used in automotive, electronic or sports applications. For that purpose, INEOS Styrolution developed and validated different high flow injection molding materials with optimize adhesion on the ***StyLight**** sheet.

Consequently, the performance of the finished part will be determined by the combination of both components, the composite ***StyLight**** "skin" and the back injected molded material. Adhesion between both components has been measured on simple rib test tools to find the optimum material properties offering strength, surface quality adhesion and high flow to fill thin ribbing design, resulting in a portfolio of short glass fiber reinforced ABS/PA blends (Terblend® N) and ABS (Novodur®), they are identified with the suffix "SL" (see Fig. 4).

		Validated for StyLight Aesthetic		Validated for StyLight Structural	
Materials for back injection	Unit	Terblend N NG-02EF SL	Terblend N NG-04EF SL	Novodur BX64137*	Terblend N NG-06EF SL
Base resin	-	ABS/PA GF	ABS/PA GF	ABS GF	ABS/PA GF
Fiber content	%	8	20	16	30
Melt Volume Rate 240 °C/10 kg	cm^3/10 min	40	30	18*	8

* In development stage

Fig. 4:** Portfolio of "SL" grades optimized for back injection molding for **StyLight composites*

Finally, above and beyond the static mechanical performance of ***StyLight****, INEOS Styrolution performed fatigue tests to evaluate the long term resistance of this new type of styrenic composite in comparison to alternative thermoplastics-based composites, as well as epoxy based composites. The results are showing the good performances of ***StyLight**** carrying a flexural load of 250 MPa after more than 2 Million cycles (tests performed by IVW, Kaiserslautern).

Surface aesthetics

Although ***StyLight**** shows a higher stiffness and a good stability versus other currently available thermoplastic composites on the market, these advantages alone would not justify the investment to develop and launch a new composite thermoplastic type on the market.

But the ***StyLight**** composite is adding another significant advantage: Its surface properties. Outstanding surface quality inherent to a styrenic matrix makes it possible to extend the application scope of composite thermoplastic to visible aesthetic parts at a competitive price level.

The lower shrinkage during the consolidation step of our amorphous styrenic copolymer matrix based on a modified SAN reduces the surface roughness ("waviness") significantly, offering a superior surface quality compared to most existing standard thermoplastic composites (see Fig. 5). INEOS Styrolution does not claim to achieve a high-end "Class A" surface in one single compression / injection shot at this point (see paragraph "Demonstrator"). Still, the surface quality achieved with ***StyLight**** - combined with the high polarity of its surface allowing an easy surface decoration process such as coating, painting or foil decoration - make it an interesting material for semi-structural aesthetic applications.

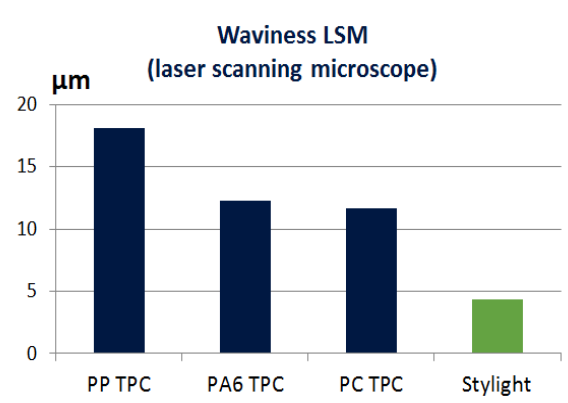

Fig. 5: *Comparative surface waviness (LMS method measured at NMF in Fürth)*

Beside the surface "flatness" advantage, the low shrinkage of the styrenic copolymer matrix is enhancing the dimensional stability of the finished parts and reduces the risk of warpage. Combined with its low water absorption the ***StyLight**** part dimension remains stable after manufacturing making it suitable for applications in vehicle interior or high tech applications requiring a good fit and finish. In combination with its good chemical resistance (environmental stress crack resistance, "ESCR"), ***StyLight**** is a robust and versatile composite solution suitable for aesthetic semi structural high performance applications.

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A Thermoplastic Composite based on a transparent matrix

This newly developed SAN based composite neither contains semi-crystalline polymer domains nor requires any additional impact modification or plasticizers. The resulting sheets have a transparent matrix and this is opening interesting aesthetic potential.

The carbon fiber woven fabric becomes now visible through the ***StyLight**** transparent matrix, offering an interesting alternative to thermoset based “carbon design” for decorative applications (see Fig. 6).

There is currently a multitude of different technologies used to provide this “carbon design” associated with high performance car racing and professional sports equipment. The most commonly used technology for this purpose is RTM based on Epoxy resins, typically cured in Autoclaves with long cycle time of multiple hours. An alternative solution used in the automotive industry for decorative parts, available typically for premium vehicles, is the impregnation with PU resin of a dry carbon fiber woven fabric previously draped on a substrate (wood or plastic). In both cases the main challenge with these technologies is to prevent the sensitive carbon fabric pattern to be disrupted during the draping and the impregnation process resulting in visible surface defects. With StyLight Aesthetic S C 200-1-100 sheet (see Fig. 2a), the layers of carbon fabric are within the SAN matrix, delivered as a laminate, limiting the risk for the fibers to move during the thermoforming process. The cycle time will be closer to a couple of minutes, and the parts can be back injection molded, resulting in a lower reject rate, labor and processing cost. Alternative transparent thermoplastic composite based on TPU or PA12 resins are typically very expensive and do not offer the high glossy surface quality of ***StyLight****. INEOS Styrolution recommends painting the surface with a clear coat to protect it from scratch, chemical and UV aggression, while enhancing further the surface quality.

Fig. 6: StyLight* *made of carbon fiber 3K twill 2/2 with clear coating*

With glass fiber woven fabrics (see Fig. 7), ***StyLight**** appears translucent with a high gloss surface finish. This is adding an interesting new feature which could be used for backlighted decorated applications at a competitive price level versus other thermoplastic or thermoset composite solutions. Automotive interior designers have now access to a new material offering structural stiffness, thin wall design, light translucency and a high surface quality, an unrivalled combination of properties opening a large spectrum of creativity.

Fig. 7: *Translucent* ***StyLight***** with glass fiber woven fabrics*

Demonstrator

In order to validate these promising laboratory results and to validate the manufacturing behavior of ***StyLight****, INEOS Styrolution decided to invest in a real size prototype mold made of steel, combining different features.

The concept of a door panel design was selected as it combines different construction, manufacturing challenges and complex shapes to demonstrate the performance of ***StyLight**** (see Fig. 8). Different surface aesthetics and a semi-structural reinforcement have been integrated in the demonstrator design.

A thermoplastic composite sheet with a thickness of 1,2 mm was chosen to provide the best compromise between weight saving, good surface quality combined with a high mechanical strength while allowing the draping of a complex shape design.

Fig. 8: *Demonstrator*

Manufacturing process

During the manufacturing process of the "demonstrator", the ***StyLight**** sheet was heated up to about 270°C. At this temperature, the composite sheet has a semi-rigid behaviour, allowing a convenient handling, positioning and draping process despite the relative complex and deep shape of the demonstrator surface. The draping phase was designed with the support and the expertise of the mold manufacturer Krumpholz Werkzeuge e. K. (Grafengehaig). The "clamping drawers" were accurately positioned in the mold, following a pre-defined moving sequence to prevent wrinkles, minimize the residual stress and the "locking" of the fiber fabrics during the part consolidation phase.

The processing parameters of the back-molded material were optimized to offer a good adhesion of the ribs to the surface of the demonstrator while filling up the frame and the overmolded upper surface of the demonstrator. The injection molding was optimized with a mold filling analysis. Rib feet were designed to offer the best surface adhesion while minimizing the visibility of the ribs on the visible side. In the demonstrator INEOS Styrolution used a high flow glass-fiber reinforced ABS/PA blend reinforced with 8% short fibers, offering a great surface quality combined with structural stiffness, low viscosity and surface adhesion to the sheet.

The optimization of manufacturing processing parameters and the draping phase have been supported by a draping process simulation performed by the company ESI (ENGINEERING SYSTEM INTERNATIONAL GmbH) based on a material card generated by the company CIKONI (TTI GmbH - CIKONI TGU). Based on these material cards basic structural simulations of static loading have also performed by ESI with ***StyLight**** on the demonstrator.

Surface decoration

One of the major challenges of the demonstrator was to take advantage of the ***StyLight**** surface property and demonstrate the feasibility to achieve a decorated surface in one single manufacturing step. We focused on two critical areas of the demonstrator: the lower part where the composite sheet is directly visible and the central part where the composite is covered and decorated directly in the mold with an insert developed by the company LEONHARD KURZ Stiftung & Co. KG (Fürth).

Different surface structures have been applied on the demonstrator: a high gloss surface finish around the loud speaker circle, a fine grain in the lower part, and a leather type grain in the upper part (see Fig. 9).

Although the ***StyLight**** sheet offers a low surface waviness measured under ideal conditions, other types of surface defects appear on the sheet surface in a complex shape of a large part. To prevent these defects the following three conditions need to be fulfilled:

- The pressure should be evenly distributed during the compressing phase over the entire visible surface, in order to allow the polymer to fill all micro cavities between fibers and to exactly reproduce the mold surface.
- A high surface temperature (150° up to 200°C) shall be maintained in the critical visible areas of the mold to allow the polymer to "close" the surface prior to cooling down and

"freezing" the polymer. A "Variotherm®" process is recommended to optimize the cycle time and to achieve best quality results.

- The part design and thickness distribution shall facilitate the draping process and prevent a stress concentration in the thermoplastic composite sheet. It is specifically critical in deep shape design, in order to avoid the risk of "fiber locking". (By "locking" we mean that the maximum angle of fibers is reached, resulting in blocking of the fabric draping and resulting in a high shear stress and surface defects.)

Fig. 9: *Details decorated insert*

In the central part of the demonstrator a foil, decorated and vacuum formed by the company LEONHARD KURZ, is decorating the reinforced fiber composite directly inside the mold during the compression phase. In order to achieve the best quality of the decorated surface, the following conditions should be fulfilled:

- The pressure should be evenly distributed during the compressing phase on the decorative foil. (Note that the mold thickness should be adapted to compensate possible thickness variations of the foil, resulting from the vacuum forming process.)
- The temperature of the ***StyLight**** sheet during the compression phase should be high enough to allow a good surface quality behind the decorative foil, while not damaging it. For this purpose, the foil was made of a high-heat ABS film with a Vicat temperature of 108°C. It is important not to bring it in contact with the ***StyLight**** sheet, which is heated up to 180°C, to prevent any foil degradation before mold closing.
- A precise positioning of the insert in the mold is essential to prevent the insert to slide during the draping phase. The draping simulation is useful for this purpose as well.

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Industry applications for the new material

The development and launch of this new material is mostly driven by the growing demand of light weight solution in the automotive industry to contribute to fuel efficiency. So far, the applications of composite thermoplastics in automotive have been focussing on the substitution of heavy structural parts typically made of steel but without any particular aesthetical value. INEOS Styrolution is convinced that there is more potential for thermoplastic composites to reduce weight in a whole new range of applications with partially visible surface.

Price remains one of the main obstacles slowing down the penetration of thermoplastic composites in the industry. The high price of the semi-finished sheet, inherent to its manufacturing and raw material cost, added to the significant upfront investment required by the part supplier to develop expertise and to acquire new tooling and handling equipment makes this innovation affordable only to a relatively small market potential.

One of the solutions to reduce system costs is to integrate structural and aesthetic functions, reducing the number of components for a given application, taking advantage of ***StyLight**** properties. For this purpose INEOS Styrolution partners with KTM, a creative engineering office to develop and propose innovative design concepts for a selected number of applications.

These selected applications are offering the highest integration potential from INEOS Styrolution's and KTM's perspective:

Automotive door module: Typically a door module comprises of three functions, an externally visible surface, typically a sheet of painted metal, a non-visible semi-structural part, typically supporting all electronic and mechatronics of the door module and insulating the cockpit from the water, and an interior visible surface. Here Styrolution is developing a concept to integrate the non-visible semi-structural function with the interior visible.

Automotive central console: This application is also very demanding with a directly visible surface, supporting electronic equipment and providing local structural stiffness. Moreover, the space available inside a console is very tight. It should allow space for the wire tree and storage space. Here again a thin wall providing structural stiffness and offering a high surface quality is offering potential for the integration of multiple functions.

Automotive lift gate: There are many lift gate designs available depending on vehicle shape and design. Different composite solutions from long glass fibre reinforced PP to SMC have been used for quite some time. Until now the interior visible surface is covering the structural frame. Attempts were made to overmold a thermoplastic composite retainer with injected molded GF PP but this is adding cost and weight. Here ***StyLight**** is offering a potential integration solution.

Body panel for trucks or tractors: A massive weight reduction is possible with the replacement of thick SMC panel currently being used in this field. But this application is more demanding than initially expected. Dimensional stability, class A surface quality, wind resistance, resistance to powerful vibrations are among the long list of specifications. Some of these panels also integrate functions like front light or bonnet. Here, ***StyLight**** may again have a good value proposition to reduce weight.

Drones: beside automotive other technical applications also require precision, aesthetic and light weight. INEOS Styrolution identified semi-professional drones as a high potential for design integration: the structural part, on which the electrical motors and the electronic steering component are mounted could be also the external housing.

For each of these different applications, alternative design solutions will be proposed, enhancing function integration, reducing the overall number of parts, striving for cost and weight reductions. These concepts will be available to INEOS Styrolution customers as of mid 2017 to inspire engineers and designers thinking “out of the box”.

Beside these System integrations, other more standard thermoplastic composite applications is recognized in electronics. The robustness of the material allows to strive for new miniaturization efforts resulting in tablets, notebooks, mobile phones and other mobile devices to lose weight, become thinner and at the same time be as stable and robust as before.

In the medical industry, prostheses and ortheses may benefit from the light and robust material. ***StyLight**** may also be considered for relatively straightforward applications like shoe inserts. In the area of toys, sports and leisure, there are multiple opportunities to take advantage of the capabilities of ***StyLight****. Ski helmets, bicycle parts like e.g. bicycle seats and drones are just a small selection of applications where the combination of robustness and aesthetic values would allow for the construction of new ideas.

Conclusion

For the first time, INEOS Styrolution developed a new type of thermoplastic composite based on an amorphous styrenic matrix. The material, named ***StyLight**** is available based on different types of textiles of woven and NCF glass and carbon fibers designed for aesthetic or structural applications. ***StyLight**** offers unique mechanical properties suitable for structural applications thanks to its very high stiffness and strength, combined with a high surface quality. ***StyLight**** will potentially extend the scope of thermoplastic composite applications to visible or decorated parts in the automotive interior or in any high performance aesthetic applications. ***StyLight**** enables automotive manufacturers to address the demand to cut on weight also in areas where aesthetics matters.

With a significant thickness reduction versus an injected moulded part resulting in significant weight reduction, such a composite solution will only be economically viable if it can integrate different functions and components into one single reinforced modular design. This integration would result in a reduction of the total number of parts, the substitution of metal reinforcements, and enables new lightweight design concepts.

***** Trade Mark application pending

About the authors

Juan started his career in 1991 at Himont in France, as application development engineer in the field of Polypropylen for the Automotive industry. He joined Dow Chemical in 1995 where he filled a number of commercial management positions in the company's engineering thermoplastic division in Germany and Switzerland.
In 2005 he joined BASF as sales manager and moved on to Styrolution in 2011 as automotive sales director for EMEA, he became Global Automotive Vice President in 2013 and since 2016 he assumed the newly created role of Composite Thermoplastic Director.
Juan received a degree in mechanical engineering from the national French school ENSAM in Paris in 1988.

Eike Jahnke started his professional career in 2010 as (Senior) Research Chemist at Styron Deutschland GmbH in Stade, Germany. In 2012, he became Technical Product Manager at INEOS Styrolution in Frankfurt. He is responsible for Luran® (SAN), Luran® HH (AMSAN), NAS® (SMMA), Styroflex® (SBC) and StyLight (thermoplastic composite).
Jahnke studied chemistry at the Freie Universität Berlin (FUB). In 2008 he received a Ph.D. at the Eidgenössische Technische Hochschule (ETH) in Zürich. He continued his academic career (postdoc) at the University of Alberta in Edmonton, Canada. In 2009, Jahnke became Akademischer Rat at the Friedrich Alexander University Erlangen/Nürnberg, Germany.

Since September 2014, Philipp Deitmerg is responsible for the business development of composites, i.e. the new *StyLight* family of products, at INEOS Styrolution.
Before his current assignment, he worked in Technical Sales for *Schrichten Kunststofftechnik* in Schmallenberg, Germany, and as Application Development Manager at the Lanxess company *Bond Laminates GmbH*.
Deitmerg completed a study in Kunststofftechnik ("Plastics Technology") at the Fachhochschule Südwestfalen in Iserlohn.