Multi-materials Composites Provide Lightweight Engineering

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Abstract
Sustainability demands materials and energy saving. As a consequence light weight engineered products are a must. This paper approaches the possibility to substitute heavy weight metal design by multi-material light weight design considering polymeric materials and employing manufacturing techniques which are optimal adapted to the materials, e.g. assembly injection moulding. The needed necessary steps for such a development are described and the conceivable result is discussed exemplarily with regard to a novel and weight saving pump housing construction.

Keywords: *Multi-materials Composites, Lightweight engineering, Assembly injection moulding, Moulded seals*

1 Introduction

Nowadays, energy efficiency is one of the most important issues for the development of future cars, which is generally demanded due to limited raw material resources, e.g. crude oil, and the necessity for reducing CO_2 emission. In dynamically driven systems energy efficiency is equal to the mass reduction with the latter finally being a light weight design issue.

Hybrid drives in automotive cars can reduce the fuel consumption of the car by assisting the engine during acceleration. There are different concepts for hybrid drives such as using an electrical or a hydraulic support device for integration into car to achieve a maximum level of efficiency [1]. In case of hydraulic support system stored braking energy, by means of pressurized oil, drives a hydraulic motor assisting the main engine of the car, when being released during acceleration. Hydraulic based hybrid drives for city trucks or busses, which undergo extreme stopping and moving drive conditions, are energy saving systems which are already available on the market. Nevertheless, the actual drawback for their applicability in normal automotive cars is their heavy duty metal construction. The hydraulic pump housing e.g. is made from cast iron and thus a heavy weight part.

Figure 1 shows an iron casted hydraulic pump housing, with its diameter of about 160 mm, which is used for a hydraulic engine. Due to its mass weight of 6.5 kg the pump housing shares the main fraction of the disadvantaging heavy weight of the complete pump.

Figure 1: Standard hydraulic pump housing from metal.

To apply a hydraulic based hybrid drive in automotive car a light weight design is essentially required and primarily the pump housing construction has to be changed in order to achieve a considerable mass reduction of up to 30%.

2 Lightweight Design

In order to substitute a standard design (Figure 1) by a lightweight design it needs to analyze the existing construction with respect to the required functionalities necessary for service use, Figure 2 [2].

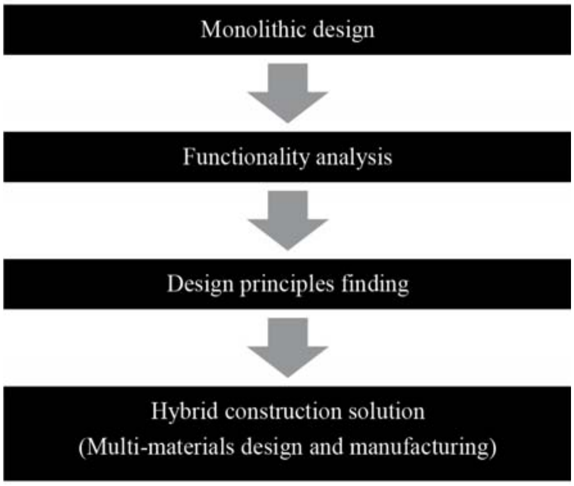

Figure 2: Re-design process steps to develop lightweight design solutions.

The standard designs are mostly monolithic constructions providing somehow a technical and economic compromise. When analyzing the required single functionalities for service application within the existing construction it is possible to find adapted design principles which can realize best the required functioning.

The established single design principles providing best solutions with regard to materials and cost efficiency (Figure 2) then in turn have to be merged in what is called hybrid construction, which considers composite structures and multi-materials design and manufacturing [3,4].

2.1 *Hybrid construction principle*

Approaching a possible lightweight solution e.g. for heavy mass weight metal construction pump a hybrid construction promises advantages. Combining a metal load bearing framework with polymeric composite part with integrated housing and sealing functionalities provides a possible solution (Figure 3) and benefits compared to the monolithic construction.

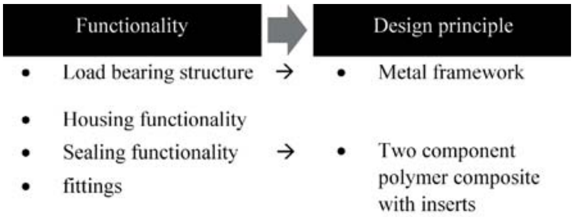

Figure 3: Adapted design principles for demanded functionalities in case of pump housing.

Figure 4: Hybrid construction of a pump housing employing multi-materials design.

Approaching design solutions for the separated single functionalities of a metal pump housing a novel construction solution can be achieved by hybrid design. It provides a total mass reduction due a partial substitution of metal by polymeric low dense material. Figure 4 shows a possible hybrid construction of a pump housing, where the load bearing functionality and the covering functionality are separated into two assembled parts. Starting from a monolithic part coming to two parts seems the first disadvantageous. But this idea allows assembly injection moulding technique to be employed for the polymeric part which in turn enables the integration of fittings and sealing elements simply into this construction without any assembly work. Consequently, the new design solution is highly effective and saves cost for assembly [5].

The multi material hybrid design provides several advantages compared to the standard metal construction. It fulfills all the application requirements at minimized total mass weight, which was verified by Finite Element method FEM strength calculation. 53% mass reduction can be achieved (Table 1), when combining a load bearing steel framework and a polymeric cover representing the housing functionality. This is due to a total mass of 3.1 kg of the hybrid solution compared to 6.5 kg of the casted monolithic construction.

Table 1: Possible mass reduction due to hybrid construction and multi-materials application

Part	Mass of part [kg] design solution	
	monolithic	***hybrid***
Housing component	6.5	0.6
Steel framework	0.0	2.5

2.2 *Framework design using topology optimization*

The framework structure which is able to carry the applied loads in application and under service conditions properly (Figure 5) can be best developed employing structural optimization [6].

Structural optimization is the subject of making a structural component to best sustain the loads at minimum compliance and what is called topology optimization. The topology optimization method is a finite element (FE) based method which solves the problem of distributing a given amount of material in a design domain subject to load and support conditions such, that the compliance of the structure is minimized. It is an introduced method used for structural optimization with respect to light weight design purpose.

With respect to load bearing purpose the original heavy weight pump housing (Figure 1) can be substituted by a filigree metal framework. This is able to carry all forces and torque moments and it provides a huge mass reduction of about 50%.

If the framework would be further made from high strength aluminium instead of steel, then a higher mass reduction is possible. The density of aluminium is about one third of the density of steel only.

The topology optimized new structure is disadvantageous perforated and cannot provide covering functionality anymore. Thus a second thin walled part with a closed surface is now needed to provide the covering functionality. Both parts are assembled together and integrated within the hybrid construction (Figure 4).

2.3 *Multi-materials composite manufacturing using assembly injection molding*

A multi material design, also in the polymer field, has its primary advantage in applying materials with best fitting properties to the local material requirements for the realization of a certain functionality of the complete structure [3,4].

Figure 5: Load bearing metal framework of pump housing developed using topology optimization method.

Metals generally provide very stiff and strong materials, whereas thermoplastic polymers can be almost freely shaped into complex geometries employing injection moulding technique. The latter is usually recommended for shell like thin walled constructions or rubberlike parts depending on whether the polymer is hard plastic or elastomeric material. Substituting steel components with density of 7.8 g/cm^3 by polymeric components can yield a mass reduction up to six times due to low density of polymers close to 1 g/cm^3.

The main mechanical loads under service application are all carried by the metal framework. In this case the pump housing itself can be manufactured from a polymeric material because it needs to withstand only low internal oil pressure up to 3 bars. A suitable polymeric material is polybuthyleneterephthalate PBT glass fibre reinforced with 30 wt% which is oil resistant material. The strength of the reinforced material is 135 MPa and sufficient to carry the calculated pressure induced stresses safe. The stress calculation was performed using the stress equation for pressurized vessel.

Using polymeric material have pros of achieving low density material, the freedom to shape complex geometry simply as well as the ability to integrate additional functionalities easily.

The developed polymeric housing in Figure 6 was actually manufactured by rapid prototyping employing stereo lithography and can be injection moulded. Injection moulding combines a series of advantages such as short cycle time and cost effective large scale production possibility. Injection moulding is also an energy efficient process when compared to metal casting, due to much lower melting temperature of the

Figure 6: Polymeric part providing the housing functionality for assembly to hybrid construction.

polymers. Furthermore, injection moulded parts can have more complex shaped geometries comparatively and are ready moulded without any after work necessary.

Required screwed joints for the connection e.g. of hydraulic piping system to the housing can be easily integrated in polymeric part using the insert technique. In addition a required radial shaft seal and static seal are needed to prevent leakage of the hydraulic oil in the use of the pump; both can be easily assembled to the polymeric part employing assembly injection moulding technique (Figure 7).

Assembly injection moulding names a two component moulding technique, which provides defined shaped and adhesively bonded multi-material composites manufactured during one process cycle. Using such manufacturing technique assembly work can be substituted and logistic efforts reduced, which finally provides cost efficiency.

The most effective two component injection moulding procedure considers a turntable mould. Employing this technique a first material component gets over moulded after being turned to a second injection position, when at the same time the first component is injection moulded at its position (starting injection position). After being solidified the over moulded part is ejected from the mould cavity in the second position. Then the mould cavity is turned to the starting position where a new moulding cycle continues.

A detail of the developed polymeric part (Figure 6) with integrated rotatory shaft seal and later manufactured by assembly injection moulding is shown in Figure 8.

The necessary seal assembly step can be substituted by employing two component injection moulding technique, which allows combining hard and soft component within one process. For the sealing functionalities an ester based thermoplastic polyurethane TPU can be used, which is oil and wear resistant soft polymer. It is advantageous in this case the connection between the polymeric housing and the sealing will be a firmly bonding, when hard and soft polymers are compatible materials.

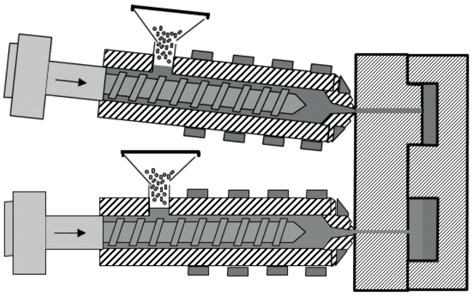

Figure 7: Assembly injection moulding principle.

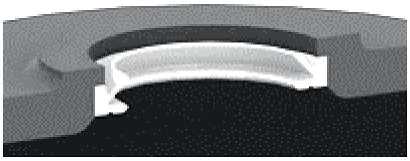

Figure 8: Polymeric part with integrated seal functionality.

The multi-material processing using thermoplastic polymers provides short cycle time within seconds and it is saving costly assembly of cross-linked rubber seal, which demands itself long vulcanization time within minutes for its production.

Table 2 shows the functionalities covered by the new developed polymeric multi-material composite part and their manufacturability.

Table 2: Polymeric housing with integrated functionalities and its realization

Functionality	Manufacturing solution
Housing	Moulded polymeric part
Sealing *static dynamic*	Assembly injection moulding
Fitting elements	Insert technique

3 Experimental

3.1 *Investigated two component part demonstrator*

In order to evaluate the suggested lightweight design and engineering process a two component part

Figure 9: Assembly injection moulded polymeric material demonstrator with integrated dynamic shaft seal.

demonstrator was designed for development of an assembly injection moulding process of a radial shaft seal integrated in a housing component (Figure 9).

Figure 10 shows a sectional view of the multi-material composite demonstrator and the necessary main requirements for the housing and sealing functionalities to be fulfilled. It consists of a hard plastic outer component and a soft rubberlike inner component where both are combined by two component injection moulding technique.

3.2 *Investigated polymeric materials*

As a possible materials combination for moulded rigid part with integrated and adhesively bonded soft seal a Polybutyleneterephthalate containing 30% glass fibre reinforcement (PBT-GF30) and an ester based thermoplastic polyurethane (TPU) [7,8] with a durometer hardness of 94 Shore A were chosen and processed using Arburg 270 injection moulding machine at different processing conditions. PBT provides stiffness, strength, thermal and oil resistance where TPU delivers wear and oil resistant rubber elastic behaviour material.

In case of two components moulding the hard component was over moulded when the mould temperature was 60°C and the melt processing temperature of the TPU was varied.

3.3 *Material testing*

3.3.1 Light microscopy

Transmission light microscopy micrographs were taken from microtome sections of different injection moulded TPU samples employing a ZEISS Axioplan 2 microscope and polarized light, in order to study their processed induced morphology. The microtome section were prepared using a cryo microtome type LEITZ RM 2165 and the thickness was of about 10 µm.

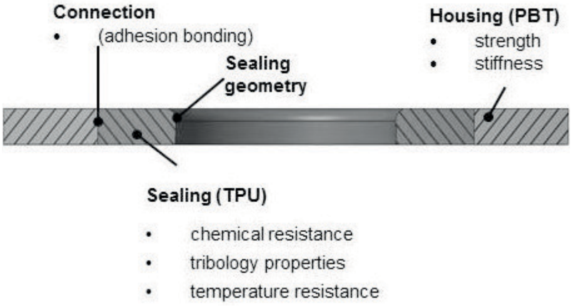

Figure 10: Requirements to moulded two component part with sealing functionality made from hard plastic and rubberlike polymer.

3.3.2 Creep test according DIN EN ISO 899-1

Creep investigations on moulded TPU specimens type 5A, according to DIN EN ISO 527-2, with a thickness of 1 mm were performed using a Zwick/Roell Z005 universal testing machine. The tension stress was set to 5 MPa and a creep experiment performed for 60 min, where the temperature was 100°C.

3.3.3 Peel resistance according DIN 1446 [9]

For the peel resistance test on two component samples were injection moulded. A hard component base plate from PBT-GF30 was over moulded with a strip like sample of TPU using a turntable mould technique. The floating roller method was employed on a Zwick/Roell Z020 for peel resistance testing. The preload of the samples was 10 N, the peeling length 108 mm and the peeling speed 100°mm/min.

3.3.4 Friction test

The friction tests on moulded TPU samples were carried out employing an Anton-paar rheometer equipped with a tribological testing setup. A steel ball

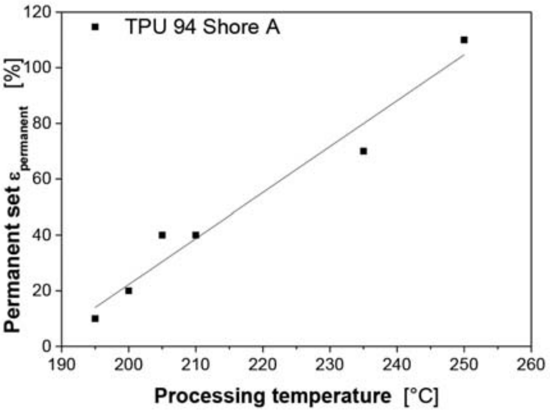

Figure 11: Relation between TPU permanent set and processing temperature.

with a diameter of 6.35 mm is used as the frictional partner with a sliding movement on the TPU samples in rotational mode. The rotational speed was varied up to 300 mm/s and a normal force was set to 10 N for testing conditions.

4 Results and Discussion

4.1 *Creep behaviour of TPU*

It is known the TPU thermo-mechanical properties depend strongly on the melt processing conditions [10] and this is the reason, why creep tests were performed on different processed TPU samples in order to quantify the dependency. The influence of the thermal process condition on the end-use properties was established as well. Figure 11 shows the influence of the TPU melt processing temperature on the permanent set of the different processed samples after 60 min creep loading condition at 100°C. The higher the melt processing temperature the higher the permanent set is measured. TPU material injection moulded at high temperature (>230ºC) behaves more viscous and shows expressed creep. Consequently for achieving best thermo-mechanical performance, the TPU has to be processed at the lowest temperature possible for injection moulding.

4.2 *Adhesion bonding behaviour of PBT/TPU*

Adhesion bonding between two polymeric materials is possible, if they are compatible. It provides a possibility to join two different moulded parts employing injection moulding process. The adhesion strength depends on the polarity of the materials and further on the interaction between them in the contact zone.

This means that beside the compatibility of the two materials, the process-conditions during two component moulding are crucial. The resulting temperature in the contact zone T_C is important when over moulding a hard component with a soft component and defines widely the adhesive bonding strength. The contact temperature T_C results from the contact between the TPU melt and the surface temperature of the PBT part being over moulded. Equation (1) shows the calculation of T_C depending on the thermal effusivity of the TPU and the PBT respectively. The thermal effusivity b is a function of thermal conductivity λ, the specific heat capacity c and density ρ of both materials [11-13].

$$T_C = \frac{b_{PBT} \cdot T_{PBT} + b_{TPU} \cdot T_{TPU}}{b_{PBT} + b_{TPU}} \tag{1}$$

Table 3 shows the calculated contact temperatures considering a thermal effusivity of 659 $W \cdot s^{1/2}/m^2.K$ for PBT and 792 $W \cdot s^{1/2}/m^2.K$ for different two component injection moulding conditions.

In case of two component injection moulding employing turntable mould the surface temperature of the PBT-GF30 hard component is equal the mould temperature, and it was manufacturing condition for the peel samples preparation. Then, the higher the melt temperature of the TPU soft component is the higher the contact temperature T_C evolves.

In order to analyse the dependence of the contact temperature and adhesion bonding, peel resistance test was used.

Table 3: Calculated contact temperatures (Eq. (1)) between PBT and TPU for different processing conditions

Surface temp. T_{PBT} [ºC]	Melt temp. T_{TPU} [ºC]	Contact temp. T_C [ºC]
80	205	148.2
80	225	159.2
80	250	172.8

Figure 12 shows a raise of the peel resistance of TPU-PBT adhesion bonds for increasing contact temperature between the two materials during over

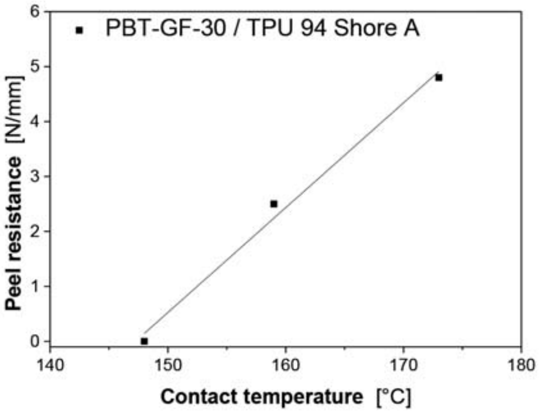

Figure 12: Relation between contact temperature during processing and peel resistance of PBT-TPU adhesion bonds.

moulding process. The peel resistance is a measure of the two components adhesion bond strength. It was observed that a better adhesion bonding can be achieved using higher TPU processing temperature, when the hard component PBT surface temperature was kept constant.

Figure 11 compared to Figure 12 shows the clear contradictive situation when targeting a strong adhesive bond between hard and soft component (PBT and TPU) on one hand, whilst the TPU as the seal material should have optimal performance under thermo-mechanical and frictional loading. A good adhesion bonding between rigid PBT and soft TPU requires a high contact temperature during over moulding the soft component. Nevertheless, settling a high TPU melt temperature, with respect to proper adhesion, it is disadvantageous for thermo-mechanical and frictional performance of the TPU material itself [14-16].

A logic solution would be to increase the surface temperature of PBT but it is not possible using such turntable mould technique in two component injection moulding. Rising the mould temperature towards higher temperature as a consequence the over moulded TPU component becomes sticky and cannot be ejected anymore from the mould cavity. Thus, for PBT/TPU combination the turntable mould technique doesn´t work in two component injection moulding. A transfer processing has to be employed, where the preheated and hot PBT hard component will be placed into the mould cavity and then becoming over moulded at relatively low melt temperature with TPU material.

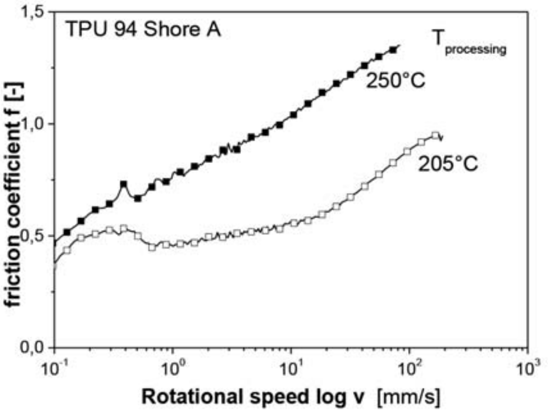

Figure 13: Stribeck curves of TPU processed at different temperatures.

4.3 *Friction behaviour of TPU*

An important issue when designing a radial shaft seal is the concern of its tribological behaviour, which has to be considered [17]. The elastomeric material needs to exhibit low friction and wear where an investigation of the tribological system between the seal and the dynamically contacting is usually required.

In general TPU is characterized with a great wear resistance, a low friction coefficient and good mechanical strength. This is why TPU is a considerable material for seals [8,18].

Figure 13 shows the Stribeck curves for TPU samples processed at different melt temperature of 205°C and 250°C.

For very low rotational speed both TPU samples show almost the same friction. But with increasing speed they differ significantly. It was noted that the friction of the 205°C processed TPU sample behaves almost constant up to approximately 100 mm/s sliding speed while the 250°C processed TPU sample presents increasing friction coefficient. It shows almost linear dependency in relation to the logarithmic sliding speed and is always much higher in comparison to the other investigated sample.

The differences between the both samples are caused by their different material morphology, which is shown in Figure 14. TPU is a segmented polymer composed of hard and soft segments, which can aggregate. Samples processed at lower temperature contain larger hard segment domains which are carrying mainly the contact load between the two frictional partners [18].

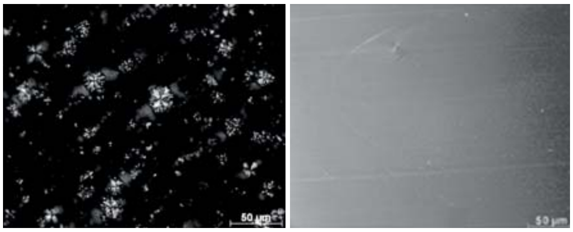

Figure 14: TPU micrographs presenting the morphology of thermally different processed samples; left: 205°C, right: 250°C processing temperature.

When the sample is processed at 250°C, the hard segment domains are comparatively much smaller and in the wavelength range of the normal light and thus no longer visible under the light microscope. This yields a more compliant material. The contact zone extents wider between the frictional partners under contact pressure, which in turn yields a rise in friction. Thus for achieving best frictional performance the TPU has to be processed at the lowest temperature possible for injection moulding. As consequence out of this a high contact temperature as a prerequisite for good adhesive bonding between hard and soft component when over moulding the hard material with the soft one cannot be achieved by processing the TPU at elevated temperature and the problem has to be solved different.

5 Tribological Testing Setup for Ring Type Samples

The friction behaviour of TPU component which provides the sealing functionality in in multi-materials composite is crucial for service application reliability and was investigated basically using a ball-plate friction test setup [19]. However such test delivers no valuable information with regard to a real sealing contact, friction and wears behaviour.

To investigate the tribological behaviour of TPU component of the assembly injection moulded polymeric material demonstrator (Figure 9) a special testing setup is required, which allows the frictional behaviour simulation under conditions similar to the service application, Figure 15.

The tribological testing principle developed provides a line contact between rubberlike tested specimen and driven cone shaped frictional partner made from steel. The resulting contact mechanics are comparable to real sealing condition. Figure 16 shows the developed testing device for further investigations of the multi-material part demonstrator.

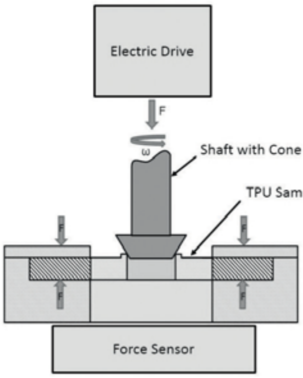

Figure 15: Tribological testing principle for ring type samples.

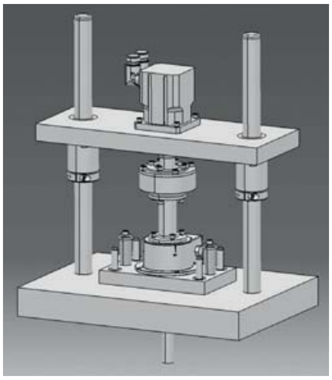

Figure 16: Tribological testing setup for ring type samples.

6 Conclusions

The paper highlights the possible advantages of multi material light weight design for high tech material and energy saving and thus sustainable constructions. Sophisticated design solutions can possibly employ a mass reduction of more than 50%, whilst guaranteeing the technical demands. The idea of lightweight engineering is shown along the possible conversion of heavy duty pump housing from metal into a light weight multi-materials composite structure.

FE based topology optimization; low dense thermoplastic polymeric materials and assembly injection moulding play an important role within that concept. The use of thermoplastic hard and soft polymers within a moulded composite structure can provide complex shaped, extreme lightweight designs with integrated functionalities.

It is found, that moulded seals from TPU material adhesively bond to hard component whilst requiring contradictive processing conditions. High bond strength needs elevated processing temperature, where low creep and friction require a minimum temperature level manufacturing. The possibility to solve problem properly is still matter of research and is mostly related to a suitable assembly injection moulding technique, which enables both processing requirements.

A new developed tribological testing setup is presented providing a line contact between the investigated material partners.

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References

[1] K. Reif, Automotive hybrid drive systems: basics, components, systems, applications, Vieweg+ Teubner, 2012 (in German).

[2] A. Frick, T. Dolde, and D. Sich, “Efficient development of high performance polymer parts using advanced simulation methods,” *Tehnomus*, vol. 18(1), pp.15-20, 2011.

[3] H. Wargnier, F.X. Kromm, M. Danis, and Y. Brechet, “Proposal for a multi-material design procedure,” *Materials & Design*, vol. 56, pp. 44-49, 2014.

[4] M. Asby, H. Shercliff, and D. Cebon, *Materials*, 3rd ed., Elsevier, 2014.

[5] F. Johannaber and W. Michaeli, *Handbook of Injection Moulding*, 2nd ed., München: Hanser, 2004 (in German).

[6] P. W. Christensen and A. Klarbring, *An Introduction to Structural Optimization*, Springer, 2009.

[7] J. Mertinkat, “New Generation of high-performance TPE,” *Sealing Technology Yearbook*, 2010, pp.55-60 (in German).

[8] D. Randall and S. Lee, *The Polyurethanes book (Huntsman Polyurethanes)*, United Kingdom: Wiley, 2002.

[9] DIN EN 1464:2010: Adhesives-Determination of peel resistance of adhesive bonds-Floating roller method

[10] A. Frick and M. Mikoszek, “Process induced micro structure evolution in polyester polyurethane and mechanical properties relationship,” *Macromolecular Symposia MMS 2012*, vol. 311, pp.57-63.

[11] T. Härtig, “Mass transfer in injection molding,” Dissertation, TU Chemnitz, 2013, pp.80-82 (in German).

[12] A. Islam, H. N. Hansen, and M. Bondo, “Experimental investigation of the factors influencing the polymer-polymer bond strength during two-component injection moulding,” *Int. J. Adv. Manuf. Technol.*, DOI 10.1007/s00170-009-2507-8

[13] D. Y. Huang and R. S. Chen, “Bonding Strength at Solid-Melt Interface for Polystyrene in a Sequential Two-Staged Injection Molding Process,” *Polymer Eng. Sci.*, vol. 39(11) pp. 2159-2171, 1999.

[14] N. Stribeck, A. Zeinolebadi, M.G. Sari, A. Frick, M. Mikoszek, and S. Botta, “Structure and Mechanical Properties of an Injection-Molded Thermoplastic Polyurethane as a Function of Melt Temperature,” *Macrom. Chem. Phys. MCP 2011*, vol. 20(212), pp.2234-2248.

[15] A. Frick, M. Borm, N. Kaoud, J. Kolodziej, and J. Neudeck, “Microstructure and thermomechanical properties relationship of segmented thermoplastic polyurethane (TPU),” 29th Intern. Conf. Polymer Processing PPS, Nueremberg, 2013, pp.11-575.

[16] A. Frick, “Influence of the microstructure on thermo-mechanical properties of thermoplastic polyurethane (TPU),” 10th Int. Scientific Technical Conference Advances in Plastics Technology APT´13, 2013, pp.718-724, ISBN: 978-83-63555-23-8

[17] S. Buhl, “Interactions in the sealing system of radial shaft sealing ring, counter surface and fluid,” Dissertation University of Stuttgart, 2006, pp.112 ff. (in German).

[18] A. Frick, M. Mikoszek, and M. Kaiser, “Quality of TPU Seals: On the Influence of morphology on the performance characteristics,” *Sealing Technology Yearbook*, 2010, pp. 356 ff. (in German).

[19] P. Heyer and J. Läuger, “Correlation between friction and flow of lubricating greases in a new tribometer device,” *Lubrication Science*, vol. 21, pp.253-268, 2009.