

Investigation of polypropylene /ultrahigh molecular weight polyethylene compounds with reinforcements and their influence on rheological and mechanical properties

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ABSTRACT

Polypropylen/ ultrahigh molecular weight polyethylene compounds with various reinforcements and fillers were compounded with a co-rotating twin screw extruder. The influence of fibers, fillers, CNT's and a compatibilizer on energy consumption during production as well the mechanical, optical and rheological behavior of the compounds were investigated by using online and offline measurement tools.

INTRODUCTION

In recent years the requirements on polymers are increasing and industry tries to develop new ways to improve the properties of them. One way to improve the properties of polymers is to mix or blend them with other polymers, additives or fillers. This possibility opens a wide range of ways to customize them to compounds which fit to the needs of the final application^{1–3}. A high-performance polymer with a high potential for future applications is ultra-high molecular weight Polyethylene (UHMWPE). With an average molecular weight (Mw) above 1 million g/mole it is used for textile, mining, chemical, machinery, medical equipment, military, and sports utility^{4–8}. The high molecular weight leads to a high number of chain entanglements, a very high melt viscosity^{9,10} and enables UHMWPE's high impact strength, toughness, abrasion resistance, chemical resistance, and self-lubrication^{11–14} but makes it difficult to process this material by standard process techniques like extrusion or injection molding. Currently the main process techniques to mold UHMWPE are compression molding, sintering, or ram extrusion^{15–18}. It could be shown that the processability of UHMWPE on a co-rotating twin screw extruder can be improved by blending it with other polyolefins like high density Polyethylene

(HDPE) or Polypropylene (PP)^{4,14}. In our last work, UHMWPE was blended with PP in various ratios and the shear and extensional viscosities during extrusion as well the influence on the mechanical properties were analyzed¹⁹. Additionally, the influence of screw design and screw speed were investigated²⁰. Superior mechanical properties for PP/UHMWPE compounds could be reached by using a shear sensitive screw. UHMWPE particles started to agglomerate by using a higher shear intensive screw. This leads us to the information that UHMWPE acts like a reinforcing filler in the PP matrix until up to high UHMWPE ratios of 75 wt%.

In this work different fillers and fibers are added to the PP/UHMWPE compounds to maximize the mechanical properties of them. Adding fibers to modify the properties of polymers is very common^{21,22}. Different fillers and fiber were used to show the various effects of PP/UHMWPE compounds. Glass fibre reinforced polyolefins have been studied multiple times for the use in the automobile industry to fabricate injection molded parts^{23,24}. Even the effect of different fiber length distributions on the mechanical properties of reinforced compounds have been studied well^{25–28} showed improved mechanical properties of glass fiber reinforced PP compounds with

increasing fiber content and fiber length. Karsli et al. 29 observed that a glass fiber reinforced PP compounds with compatibilizers showed superior mechanical properties because of increased adhesion between unipolar PP molecules and polar glass fibers. Because of the carbon-nano-tubes (CNTs) estimated E-Modulus of 1000-2000 GPa, CNTs are commonly used to increase the hardness of polymeric materials to enable outstanding mechanical properties 30–33.

The dispersion as well as interfacial adhesion of CNTs and the polymer matrix are counted as the main factors for the optimization of the reinforcement effect 34,35. Because of strong van der Waals attractions resulting out of the huge specific surface CNTs tend to form agglomerates. Abdolmaleki et al. and Cha et al. 36,37 describe techniques as surface modification of the CNTs to reach better dispersions. Calcium carbonate (CaCO_3) is a commonly used filler in the polymer industry, especially for polyolefins. CaCO_3 is often used as cheap filler at high loadings. Zebarjad et al. 38 showed a decrease in tensile strength and elongation at break while the E-Modulus of CaCO_3 /PP compounds rises. Leong et al. 39 believe that the reduction of mechanical properties is caused by an immobilization of molecular chains of PP because of the CaCO_3 particles. Another common way to reinforce polyolefins is blending them with carbon fiber (CF) which are known for their high specific modulus, tensile strength and stiffness. Further CF awake the interest of many researches because of their light weight and high conductivity 40,41. Rezaei et al. 42 compared CF reinforced polypropylene's tensile strength values to carbon steel for bonnet application. Additionally, it was discovered that an increase in fiber length can enhance thermal stability on the compounds. Fu et al. 43 did basic investigations on the effect of fiber length and fiber content on tensile properties of CF reinforced polypropylene. Only little work to investigate the improvement of mechanical properties by adding compatibilizers like maleic anhydride was done by Li et al. 44. Karsli et al. 45 could show that CF reinforced PP with compatibilizers have higher values for tensile strength and E-Modulus.

EXPERIMENTAL

Materials and Compounding

UHMWPE was supplied in powder form (particle size according to ASTM D 1921 is

150 μm) by Braskem Petrochemical RS, Brazil. It had an average molecular weight of 3.0×10^6 g/mol and a density of 0.925 g/cm³. The used PP homopolymer, supplied by Braskem Petrochemical RS, Brazil, was a reactor grade with a melt flow rate of 4.2 g/10min (2.16 kg/230°C) and a density of 0.905 g/cm³.

To guarantee thermal stability and stable processing a 0.5 weight percent mixture of additives was added to each sample. For improved handling and homogeneity, part of the raw materials was premixed with a Speedy TM – mixer (Mixaco Maschinenbau Dr. Herfeld GmbH & Co. KG, Neuenrade, Germany). Polybond 3349 was supplied by SI Group, New York, USA. It was a maleic anhydride modified linear low density polyethylene (LLDPE) with a MFR of 8.0 g 10 min⁻¹ (2.16 kg / 190°C) and a density of 0.93 g cm⁻³. The melting point is at 123°C and the bulk density is 0.6 g cm⁻³. The calcium carbonate calcipore T by Reverté, Barcelona, Spain was used. The average particle size is 1.2 μm and the bulk density is 0.55 kg/dm³. For the trials K-Nanos 100T CNTs by KUMHO petrochemicals, Seoul, South Korea were used.

The diameter is between 10 to 15 nm and the bulk density is 0.02 to 0.04 g ml⁻¹. The CNTs are bundled to bundles with a diameter of 3 to 15 μm and a length of 10 to 50 μm . Carbon fibers were supplied by DREYPLAS, Meerbusch, Germany. The CF are a Polyacrylnitrile type and have a length of 6 mm. The fiber diameter varies between 5 to 7.5 μm and the bulk density is about 300 g cm⁻³. In addition, Glas fibers Type Thermo Flow 636 from Johns Manville with a length of 4 mm and a diameter of 13 μm were used.

Table 1 shows the composition of the samples tested in this publication. The samples are described briefly by a code, where P stands for polypropylene, U for ultra-high molecular weight polyethylene, the first pair of numbers for the weight percent of P and U, the second number for screw speed of the extruder and N2 for the use of an inertisation with nitrogen at the feed during extrusion process, to get a better overview.

Early research by Unger et al. 46 showed that a nitrogen inertisation prevents degradation of the polymers. Prohibiting degradation ensures a better comparability of different samples extruded with different screw geometries and screw speeds. The specific energy input (SEI)

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shows how much energy is necessary to extrude one kilogram of the final material and is an indicator for the shear stress the compounded material experiences during processing.

Table 1: Recipes of the PP/UHMWPE samples extruded with different fillers at various screw speeds.

Sample	PP [wt%]	UHMWPE [wt%]	Additives [wt%]	Filler [wt%]	Polybond 3349 [wt%]	Process setup [/]	Screw speed [rpm]
50/50	49.75	49.75	0.5	0	0	A	200
50/50- GF-200	47.25	47.25	0,5	5% GF	0	A	200
50/50- GF-400	47.25	47.25	0,5	5% GF	0	A	400
50/50 - CNT	47.25	47.25	0,5	5% CNT	0	A	200
50/50 – CaCO ₃	47.25	47.25	0,5	5% CaCO ₃	0	B	200
50/50- CF	47.25	47.25	0,5	5% CF	0	A	200
PB-50/50	47.25	47.25	0,5	0	5	A	200
PB-50/50- GF-200	44.75	44.75	0,5	5% GF	5	A	200
PB-50/50- GF-400	44.75	44.75	0,5	5% GF	5	A	400
PB-50/50 – CNT	44.75	44.75	0,5	5% CNT	5	A	200
PB-50/50 – CaCO ₃	44.75	44.75	0,5	5% CaCO ₃	5	B	200
PB-50/50- CF	44.75	44.75	0,5	5% CF	5	A	200

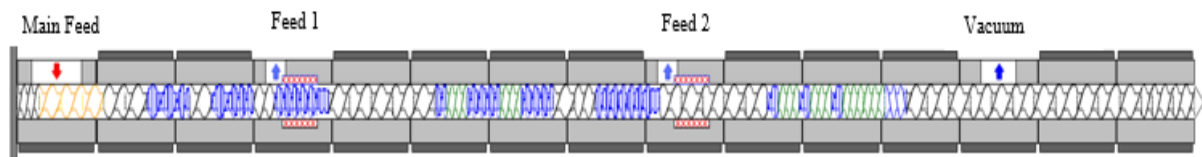


Figure1. Setup of Screw S3. Side feeder cylinder 4 and 9 w.o. venting. Vacuum cylinder at position 13. Black: Transport elements, blue: Kneading blocks, green: Mixing element²⁰.

For compounding a ZSE 27 MaXX to rqueintermeshing co-rotating twin screw extruder with an outside /inside diameter ratio of 1,66 and a specific torque level of 12.5 Nm/cm³ (Leistritz Extrusionstechnik GmbH, Nuremberg, Germany) was used. The process length was 60 L/D (see Figure 1) which means 15 barrel elements, each with a length of 4 L/D (Figure 4.b.). On the third to last barrel vacuum (-900 mbar) was applied by using a water ring pump. The temperature profile was set between 200 and 220°C and the screw speed was set between

200 and 400 rpm with a throughput of 10 kg/h. Figure2 and Figure3 show the different positions of the side feeders for fillers and fibers. The side feeder for fillers is at barrel element 5 at the beginning of the screw to enable a good incorporation of the fillers which is shown in Figure2. Contrary to fillers, fibers need to be added at the end of the process so they don't get broken during kneading of the polymer melt. For this reason, fibers were added in barrel element nine, which is shown in Figure3.

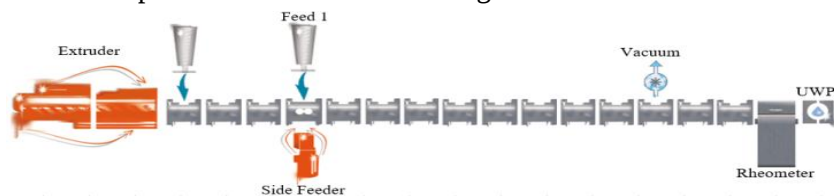


Figure2. Process setup A of extruder, rheometer and underwater pelletizer (UWP). The side feeder is located at barrel element 4.

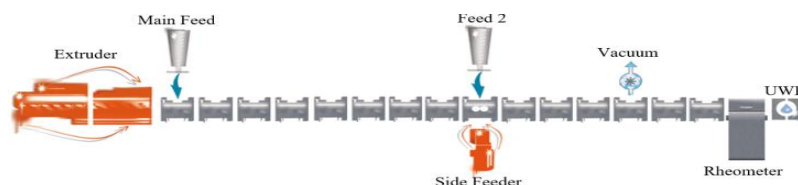


Figure3. Process setup B of extruder, rheometer and underwater pelletizer (UWP). The side feeder is located at barrel element 9.

Figure 3 show the used screw configuration. At the beginning the screw is designed to melt the polymer materials and blend them with the additives. At barrel 5 the incorporation zone starts and the screw was equipped with additional kneading blocks (Figure 4.c.) and mixing elements (Figure 4.d.). Between the functional zones conveying elements (Figure

4.a.) for material transport and pressure build up were installed. The outside screw diameter D_o of a ZSE27MaXXtorque is 28.3 mm. For simple upscaling of extrusion processes, the length of a barrel element l_b equals four times the outside diameter of one screw element as seen in Error! Reference source not found. b.

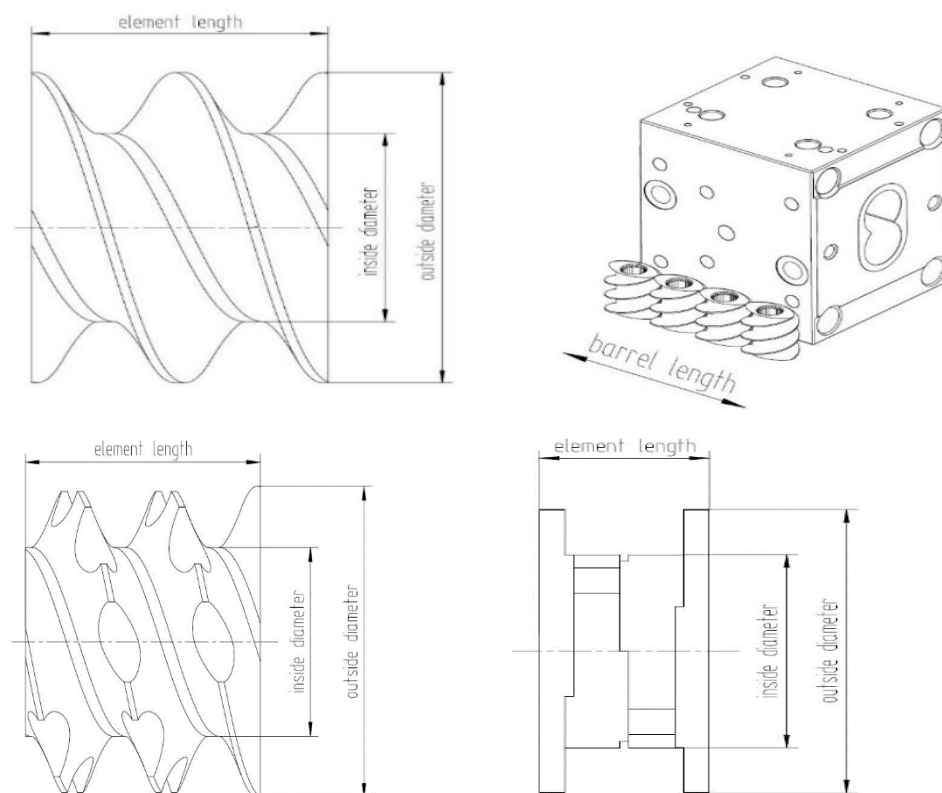


Figure 4a. Schematic drawing of a conveying element **b.)** Schematic drawing of a barrel element and four conveying elements **c.)** Schematic drawing of a kneading block **d.)** Schematic drawing of a mixing element.^{19,20}

A die head with three holes of 3.5 mm diameter was used in a combination with an underwater pelletizer EUP 150 (ECON GmbH, Weißkirchen, Austria) for pelletizing the compounds.

The melt quality in form of shear and extensional viscosity was examined by using an inline rheometer, LDR11 (Leistritz Extrusionstechnik GmbH, Nuremberg, Germany).

Thanks to the proprietary slit die which is divided into three sections it is possible to measure shear viscosity as well as extensional viscosity based on a constant average extensional rate 47,48.

As described by Luger et al. 49–51 measured data points were corrected according to Cogs well and Weissenberg- Rabinowitsch.

All viscosity data points are the average of 60 seconds of stable melt flow¹⁹.

Injection Molding

IZOD impact strength testing bars with a length of 80 mm, width of 10 mm and thickness of 4 mm and Tensile testing bars (type 1A) with a total thickness of 4 mm, width of 10 mm at measurement point and total length of 120 mm were produced by injection molding with an Ergotech-compact 350-120 (Sumitomo (SHI) Demag, Schwaig, Germany) injection molding machine. The temperature profile (see Table 2) was held constant for all samples to ensure constant processing conditions. The tool temperature, 95°C, injection speed, 10 mm/s, and cooling time, 60 seconds, were hold constant to enable similar thermal and mechanical history for every injection molded

part. The holding pressure was 500 bar and the holding pressure time was 15 s. Before mechanical testing, the injection molded

samples were conditioned for 5 days at room temperature.

Table2. Temperature profile of injection molding process for various PP/ UHMWPE compounds.

Temp. Zone 1 [°C]	Temp. Zone 2 [°C]	Temp. Zone 3 [°C]	Temp. Zone 4 [°C]	Temp. Zone 5 [°C]
40	215	220	225	230

Tensiletesting DIN EN ISO 527 1-2 52,53

The tensile bars were tested in the universal testing machine 3366 with a maximum force of 10 kN (Instron, Norwood, USA). The specimen was pulled apart with a test speed of 50 mm/min. The distance of the clamps and the measured force is documented and evaluated during the tensile test. For every sample a minimum of 6 specimen was tested and five samples were taken for the evaluation of the material parameter.

IZOD Impact Testing DIN EN ISO 180 54

For IZOD testing an impact pendulum with a force of 11 J and an impact velocity of 3,46 m/s was used (CEAST 9050 by Instron, Norwood, USA). The specimen with a length of 80 mm, width of 10 mm and thickness of 4 mm was notched once (2 mm deep) with a manual notching machine (C-6897 by Instron, Norwood, USA) so the width decreases to 8 mm. For impact strength testing the energy absorbed by the specimen during the impact was measured. Further, the geometrics and the type of break of the specimen were documented. For each sample 6 specimen were tested and evaluated.

Differential Scanning Calorimetry (DSC)

For differential scanning calorimetry a DSC-3 (Mettler Toledo, Columbus, USA) was used. The samples were heated from 0°C to 200°C with a heating rate of 10 K min⁻¹. All samples were tested under a Nitrogen atmosphere.

Scanning Electron Microscopy (SEM)

IZOD impact tested specimen was investigated with the field emission scanning electron microscope SUPRA 40/40VP (Carl Zeiss SMT, Oberkochen, Germany). Before, the samples

breaking areas were Argon inerted and sputter-coated with a thin gold layer. Incomplete broken samples had to be cut through carefully. Only the area broken while impact testing was examined.

RESULTS AND DISCUSSION

Specific Energy Input (SEI)

Figure5shows the evaluation of the specific energy input for all extruded samples. SEI represents the amount of energy used to extrude 1 kg of material. It is calculated from extruder torque (M_{act}), maximum extruder torque (M_{max}), actual screw speed (n_{act}), maximum screw speed (n_{max}), nominal power (P_{nom}), an efficiency of 0,97 and feedrate ($\dot{m}$) using equation (1)55,21,22:

$$SEI = \frac{M_{act}}{M_{max}} \cdot \frac{n_{act}}{n_{max}} \cdot \frac{P_{nom} \cdot 0,97}{\dot{m}}$$

Figure 5 shows that the SEI increased by using 5 wt.% of Polybond. As expected, the SEI decreases by using 5 wt.% of calcium carbonate as a filler. For glass fibers, carbon fibers and CNTs the SEI increases in comparison to pure PP/UHMWPE. Of course, the SEI of the PP/UHMWPE sample with glass fibers which was extruded at 400 rpm is higher as the sample extruded at 200 rpm. This shows that the fibers experienced higher shear forces by the screw. The SEI of the CNT filled compound is higher than the CF and GF filled compound. The CNTs show the highest SEI value because of the decreased flow ability of the compound. As seen in Figure10 and Figure11, the CNT filled 50/50 PP/UHMWPE compound have the highest true shear and elongation viscosity of the tested compounds.

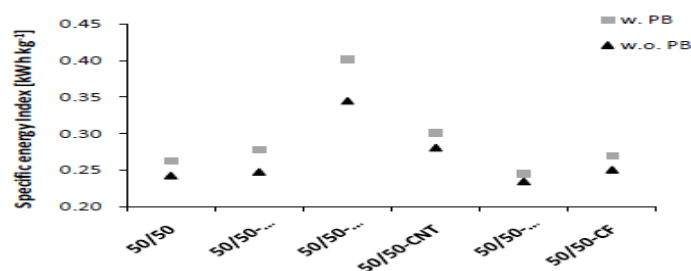


Figure5. SEI of 50/50 PP/UHMWPE Compounds produced with various fillers and w./w.o. Polybond 3349.

Rheology

The evaluation of the rheological data shows the influence of Polybond 3349 on the 50/50 (PP/UHMWPE) and on the CNT filled compound. In both cases Figure6 and Figure7 show that the use of Polybond 3349 results in an

increase of true shear viscosity and elongation viscosity for both formulations. This shows us that the use of PB in general increases the true shear and extensional viscosity.

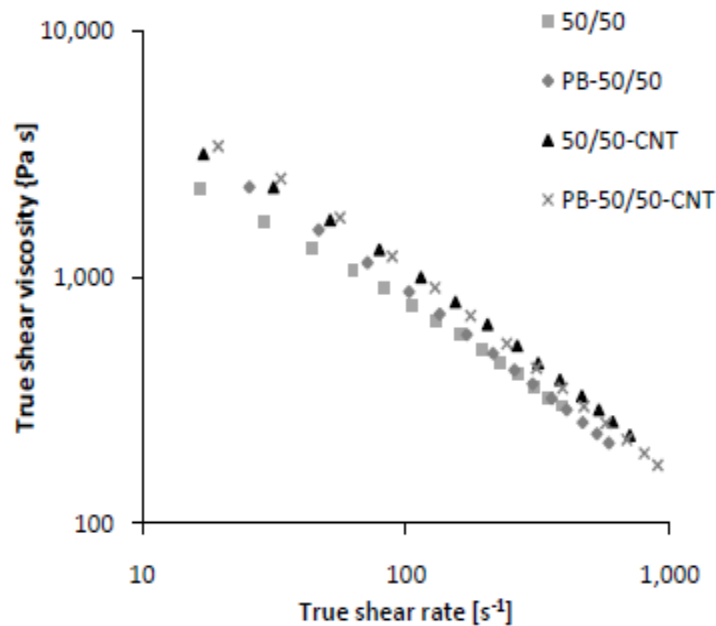


Figure6. Comparison of the true shear viscosity of the 50/50 (PP/UHMWPE) and the CNT filled compound with and without Polybond 3349.

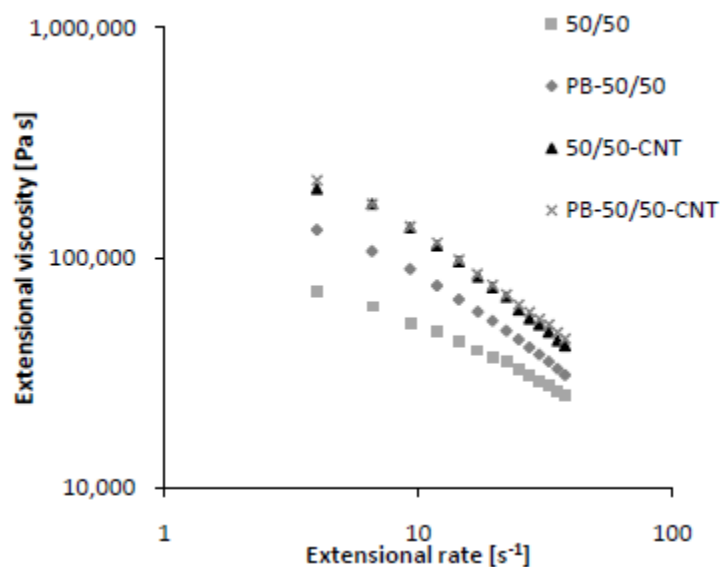


Figure7. Comparison of the extensional viscosity of the 50/50 (PP/UHMWPE) and the CNT filled compound with and without Polybond 3349.

Figure8 and Figure9 show the effect of the rotation speed of the screw on GF filled PP/UHMWPE compounds. As expected, the true shear viscosity and the extensional viscosity decrease with increasing screw speed. Higher screw speeds break the glass fibers into smaller

fibers and therefore the viscosity of the compound decreases. However, extensional viscosity is more sensitive to the decrease of fiber length than shear viscosity. Trouton-Ratio, equation (2) by Trouton 56, says that a Newtonian polymer's extensional viscosity

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η_{ext} is approximately three times its shear viscosity η_{shear} . Therefore, it is expected that the effect of molecular weight can be observed

$$\eta_{\text{ext}} \approx 3 \cdot \eta_{\text{shear}}$$

in the extensional viscosity before the shear viscosity what could be shown here.

(2)

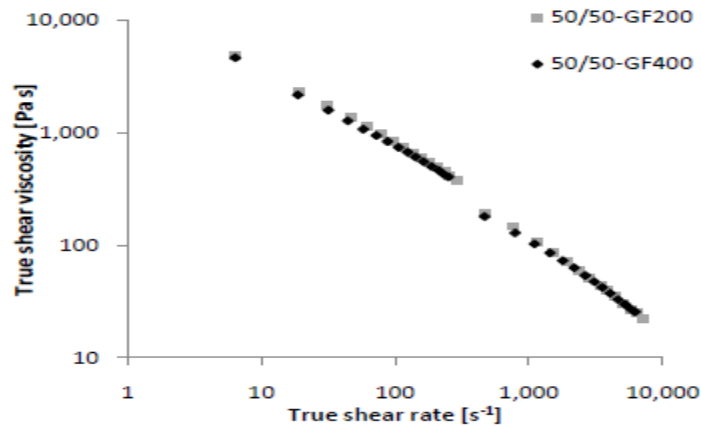


Figure8. Comparison of true shear viscosity of GF filled compounds extruded at screw speed of 200 rpm and 400 rpm.

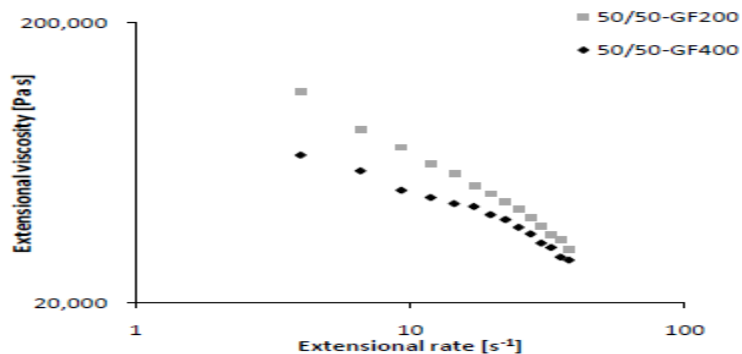


Figure9. Comparison of extensional viscosity of GF filled compounds extruded at screw speed of 200 rpm and 400 rpm.

In general Figure10 and Figure11 show that the true shear viscosity and the extensional viscosity

rise from sample 50/50 to 50/50-CaCO₃ to 50/50-GF to 50/50-CF to 50/50-CNT.

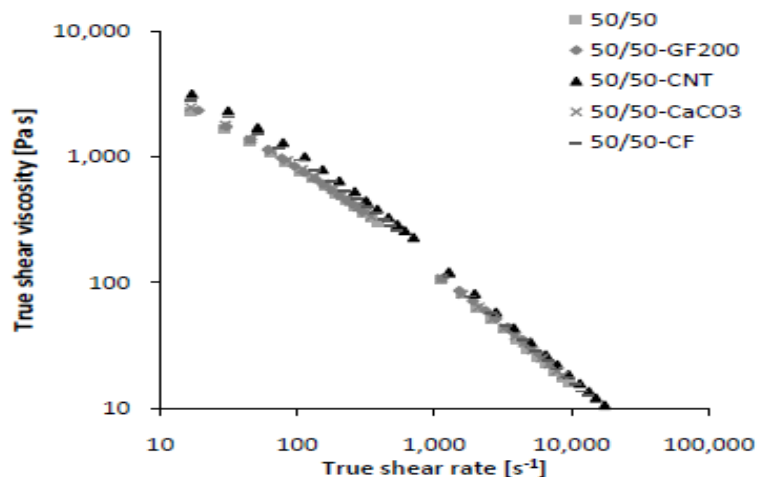


Figure10. Comparison of true shear viscosity of 50/50 PP/UHMWPE Compounds produced with several screws at screw speed of 200 rpm at a temperature of 220°C.

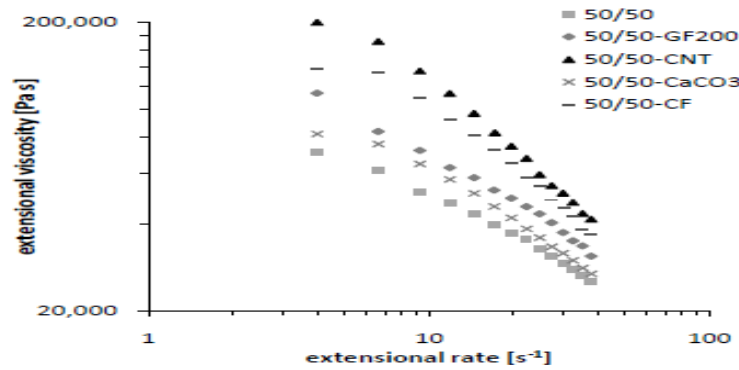


Figure11. Comparison extensional viscosity of 50/50 PP/UHMWPE Compounds produced with several screws at screw speed of 200 rpm at a temperature of 220°C.

Tensile Test

The tensile tests show the behavior of the injection molded material under tensile stress. The specimen is deformed at a constant rate while the force is recorded. To compare the measurements of different samples the tensile stress σ (Eq. 3) is evaluated out of the pulling force F and the area A of the specimen.

$$\sigma = \frac{F}{A}$$

The elongation ε (Eq. 4) is calculated by dividing the traveled distance L with the length between the clamps at the beginning of the test L_0 :

$$\varepsilon = \frac{L}{L_0}$$

The tensile strength is evaluated at the first maximum of the tensile stress curve and indicates the maximum tensile stress a material can withstand. Additionally, the point of failure is determined. The E-Modulus E_t is a measure of material stiffness. E-Modulus is calculated from the slope at the beginning of the tensile test according to Eq. 5:

$$E_t = \frac{\Delta\sigma}{\Delta\varepsilon}$$

In Figure12 tensile tests show the influence of the fillers and fibers on the 50/50 PP/UHMWPE compounds with and without compatibilizer. Considering Figure12 the tangent E-Modulus rises by using all fillers and fibers. This means that the stiffness increases by adding fillers and fibers to the PP/UHMWPE compounds. Especially the values for GF (1505 Pa s) and CF (1457 Pa s) increased rapidly regarding the value of the pure PP/UHMWPE compound (1049 Pa s) without compatibilizers. CNTs (1144 Pa s) and CaCO₃ (1099 Pa s) increased the materials stiffness as well but less than fibers. This is caused by the size and geometry of the fibers. During injection molding the fibers get orientated into the direction of injection which is as well the pulling direction during tensile testing. This effect makes the fibers an even better addition for PP/UHMWPE compounds than fillers regarding the E-Modulus. Adding 5 wt.% of compatibilizer (PB) does not affect the E-Modulus noticeable. The E-Modulus for GF and CF increase a little bit due to the use of the compatibilizer. There is no effect or even an increase of the E-Modulus for CNTs and calcium carbonate.

(Eq. 5)

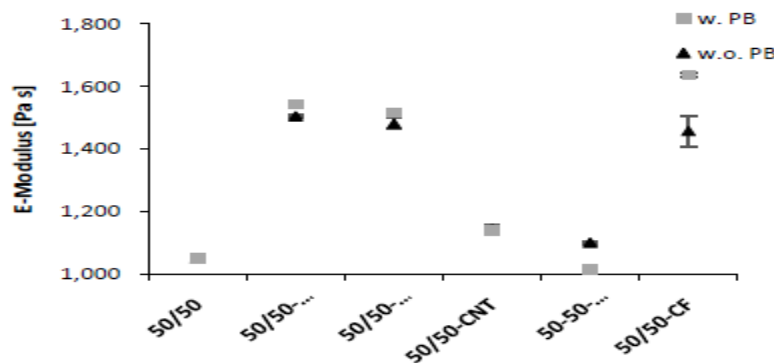


Figure12. E-Module of 50/50 PP/UHMWPE Compounds produced with various fillers and fibers at 200 and 400 rpm with and without compatibilizer (PB).

Figure13 shows the influence of the fillers and fibers on the tensile stress of the compounds. The tensile stress gives information about the maximum force during the tensile tests. Here all fillers and fibers improved the tensile stress except calcium carbonate. Calcium carbonate does not strengthen the compound because of its high polarity. The compound is unpolar what results in a disaffection of the filler with the compound. On the other hand, CNTs as a filler show increased tensile stress in comparison to the raw compound. This is caused by good polar-polar interactions of CNTs and the compound and because of the high tensile stress of CNTs itself. Fibers increase the tensile stress of the PP/UHMWPE compound as well. Glass

fibers extruded at a screw speed of 200 rpm show a higher tensile stress than glass fibers which were extruded at screw speeds of 400 rpm. This is caused by higher screw speeds breaking the fibers and a decrease of the fiber length distribution. Carbon fibers also show an increase of tensile strength compared to the raw compound. Again, this is caused by the high tensile stress of the carbon fibers themselves. Adding the compatibilizer drops the tensile stress of the raw compound itself. For GF and calcium carbonate adding the used compatibilizer results is a negative effect on the tensile stress. The CNT and CF filled compound's tensile stress increases slightly for the samples where the compatibilizer was used.

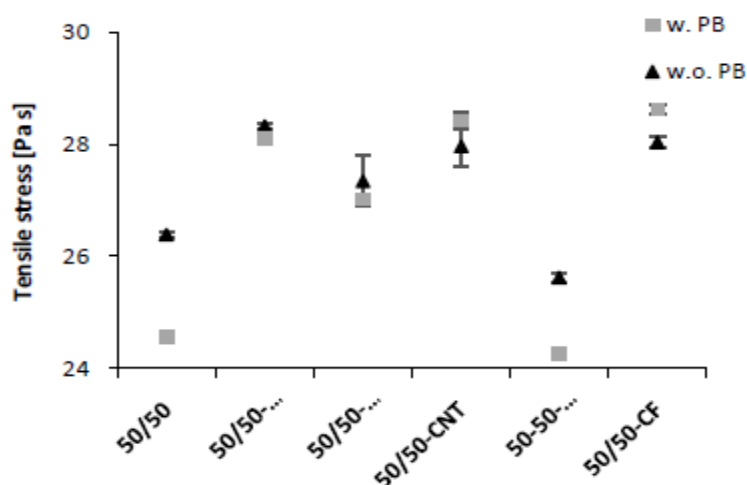


Figure13. Tensile stress of 50/50 PP/UHMWPE Compounds produced with various fillers and fibers at a screw speed of 200 and 400 rpm with and without compatibilizer (PB).

In contrast to E-Module and tensile stress the elongation at break was not affected that much by the use of fillers and fibers. Only the compound which was extruded with glass fibers at 400 rpm shows a significant increase of elongation at break. This might be caused by a better incorporation of the GF at higher screw speeds. At higher screw speeds the shear rate which is on the polymer is higher, too. For that reason, there is a drop of viscosity during extrusion. Lower viscous polymer melts show a better wetting behavior than high viscous melts. The elongation at break values for the glass fiber compound extruded at 200 rpm screw speed decreases. The addition of 5 wt.% CNTs, calcium carbonate and carbon fibers to the PP/UHMWPE compounds did not affect the elongation at break significantly. The elongation at break values decrease rapidly for the samples which were compounded with 5 wt.% of compatibilizer. This shows us that the specimen

got very brittle and were not resistant against stretching forces anymore. The decrease in elongation at break suggests that something is changing in morphology and phase. HDPE and LDPE can form separate phases depending on how similar they are. HDPE and LDPE do not co crystallize normally. Finally, the tensile tests show a huge influence of glass and carbon fibers on the PP/UHMWPE compounds for E-Modulus and tensile strength. CNTs could increase the E-Modulus and the tensile strength of the compound as well without affecting the elongation at break. Calcium carbonate did not improve the tensile behavior of PP/UHMWPE compounds. Here even the tensile stress decreased. Generally, the addition of the used compatibilizer does not affect the E-Modulus or tensile stress in a significant positive way. The elongation at break values dropped to a minimum for the samples which were compounded with 5 wt.% compatibilizer.

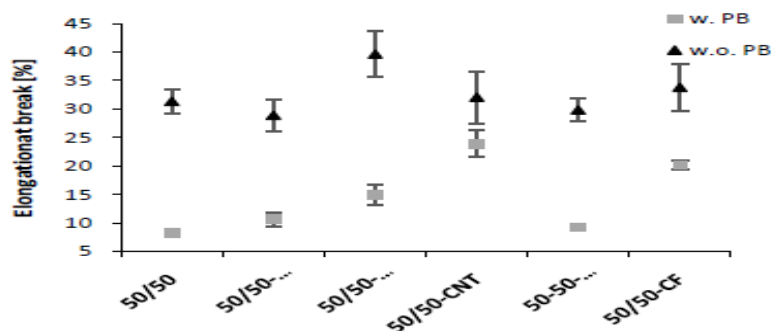


Figure14. Elongation at break of 50/50 PP/UHMWPE Compounds produced with various screw configurations at screw speeds of 100, 200 and 300 rpm with and without compatibilizer (PB).

IZOD Impact Testing

IZOD impact tests in Figure15 show an increase of notched impact strength for PP/UHMWPE compounds extruded with 5 wt.% of CNTs and carbon fibers. The notched impact strength of GF and calcium carbonate filled samples decreased compared to the pure polymer compound. This curve might be caused by the fact that GF and calcium carbonate are polar whereas the CNTs and CF are unipolar. Therefore, the mixing properties and the adhesion of the compound to CNTs and CF is better than to polar substances. This thesis is supported by the fact that the PP/UHMWPE compound with 5 wt.% of GF extruded at 400 rpm shows better notched impact values than the

ones extruded at 200 rpm. Higher screw speeds lead to better mixing of the compound with the fillers and fibers. In addition, the GF show a lower fiber length distribution at 400 rpm screw speed what means that there are more small fibers. It is well known that the mechanical properties show better results for smaller particle sizes of fiber length distributions. Again, adding the used compatibilizer does not affect the results of the notched impact tests of the PP/UHMWPE compounds with different fibers and fillers in a positive way. The value of the raw PP/UHMWPE compound alone dropped for over 50% due to the use of the compatibilizer.

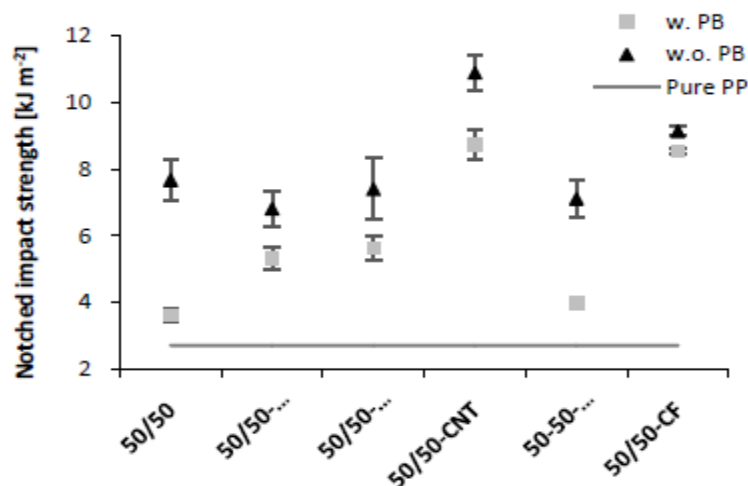


Figure15. Notched impact strength of pure PP and 50/50 PP/UHMWPE Compounds produced with various screw configurations at screw speeds of 100, 200 and 300 rpm with and without compatibilizer (PB).

Differential scanning calorimetry

DSC measurements from 0°C to 200°C and a heating rate of 10 K min⁻¹ were conducted for the 50/50 PP/UHMWPE sample with and without the compatibilizer. The DSC curves in Figure16 show two significant exothermal signal peaks for UHMWPE at approx. 135°C

and for PP at approx. 165°C. Due to the use of Polybond 3348 the polyethylene peak temperature was switched from 136,25°C (50/50) to 133,71°C (PB-50/50). The polypropylene peak temperature is nearly the same with 165,58°C (50/50) and 165,10°C (PB-50/50). The change in peak temperature for the polyethylene peak might be caused because

Polybond 3349 comes as a Maleic anhydride modified LLDPE. The LLDPE is likely to lower the peak temperature for the polyethylene peak. The crystallinity of PP XPP / UHMWPE XPE is calculated in Eq. 6. Here the total heat of melting for PP Hm,PP / UHMWPEHm,PE is divided by the heat of melting of 100 % PP H100, PP / UHMWPE H100,PE. The total heat of melting for PP Hm,PP / UHMWPEHm,PE is calculated in Eq. 7 by dividing the Peak Area of PP HPP / UHMWPE HPE by the mass of PP mPP / UHMWPE mPE for the sample. The heat of melting for 100 % crystalline PP is 165 J g⁻¹ and for PE 289,3 J g⁻¹.

$$X_{PP/PE} = \frac{H_{m,PP/PE}}{H_{100,PP/PE}} \cdot 100 \quad (\text{Eq. 6})$$

$$H_{m,PP/PE} = \frac{H_{PP/PE}}{m_{PP/PE}} \quad (\text{Eq. 7})$$

The crystallinity for PP/PE without compatibilizer is 74,8%/24,9% and the crystallinity for PP/PE in the sample with compatibilizer is calculated to 77,7%/22,9%. The effect of the compatibilizer is that the crystallinity of PP increases whereas the crystallinity of the PE decreases. This might be caused by the compatibilizer working as some kind of nucleation agent. Further investigations on the crystallization process of PP/UHMWPE compounds were conducted by Unger et al.19.

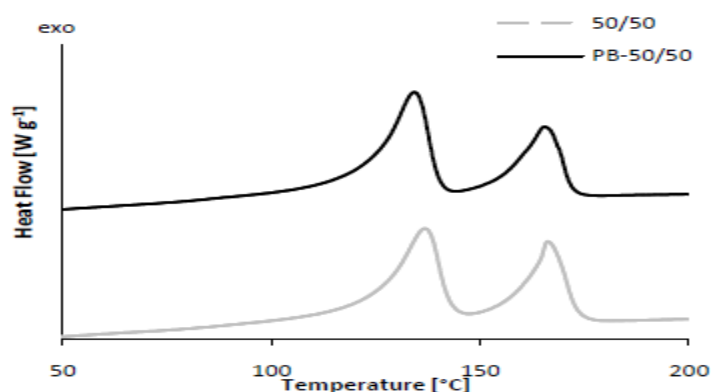


Figure16. First heating curves of 50/50 (PP/UHMWPE) compounds w. and w.o. compatibilizer determined by DSC.

Optical Evaluation

Figure17 to Figure22 show SEM pictures of the breaking area of notched impact tested PP/UHMWPE compounds with 5 wt.% of different fillers. Figure17 shows the raw 50/50 PP/UHMWPE compound. Here a very rough breaking surface can be seen. The PP matrix appears as a light grey surface with darker spots (voids) and lighter particles sitting on the surface.

It is likely the particles are UHMWPE that has pulled out of the PP matrix during fracture, leaving behind the voids. These UHMWPE particles do not appear to deform during sample failure. The lack of particle deformation and deformation in the PP around the voids, indicates poor adhesion between the UHMWPE and PP materials. Figure 18 to Figure22 show the PP/UHMWPE compounds with calcium carbonate, GF, GF with compatibilizer, CF and CNTs. Calcium carbonate can be seen as small white dots on the PP/UHMWPE surface in Figure 18. It seems like they do not influence the

breaking surface of the compound. In Figure19 and Figure 20 GF standing out of the breaking area can be observed. Additionally, smaller holes which show spots where GF were pulled out of the surface can be seen. Figure 20 shows that the compatibilizer increases the adhesion between GF and the polymer matrix.

Here the polymer wets the fibers much better than in Figure19 where no compatibilizer was used. Figure 21 shows a similar picture for PP/UHMWPE compounds with 5 wt.% of CF. Again, fibers and holes of fibers which were pulled out of the matrix can be seen. The CF are much thinner than GF.

Regarding Figure19 to Figure 21 one can see that the fibers are just connected to the PP matrix. No picture showed fibers sticking to the UHMWPE particles which can be seen.

Figure22 shows the PP/UHMWPE compound with CNTs taken at a magnitude of 14000x. One can easily see that the CNTs are well incorporated in the polymer surface.

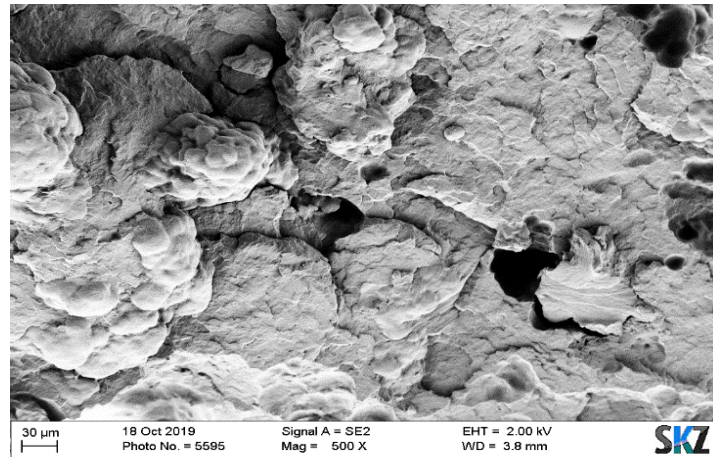


Figure17. SEM photograph with a 500x magnitude of the breaking area of a 50/50 (PP/UHMWPE) sample which was impact strength tested

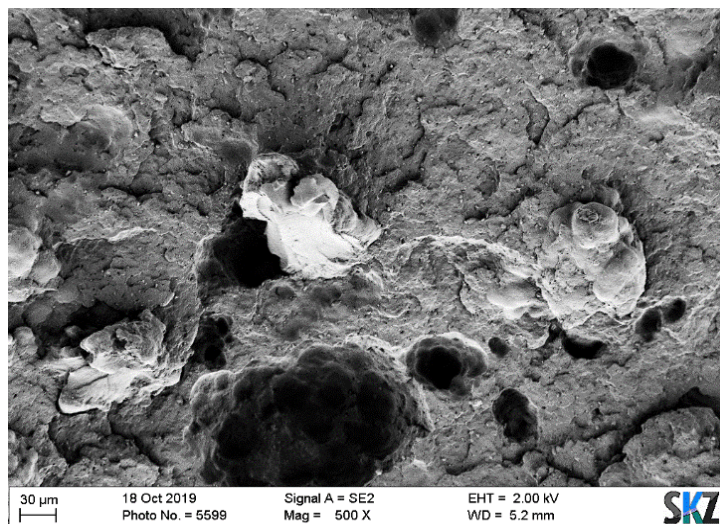


Figure 18. SEM photograph with a 500x magnitude of the breaking area of a 50/50 (PP/UHMWPE) sample with 5% CaCO₃ which was impact strength tested.

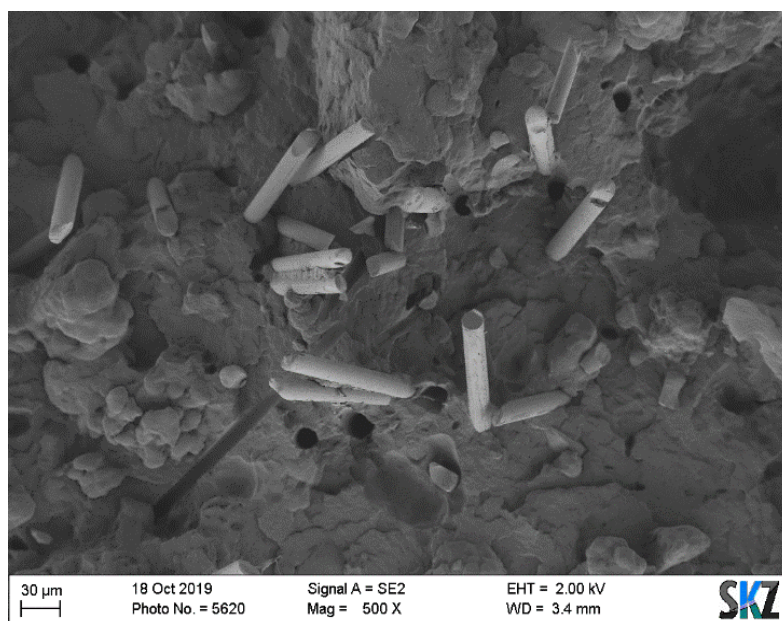


Figure19. SEM photograph with a 500x magnitude of the breaking area of a 50/50 (PP/UHMWPE) sample with 5 % glass fiber which was impact strength tested.

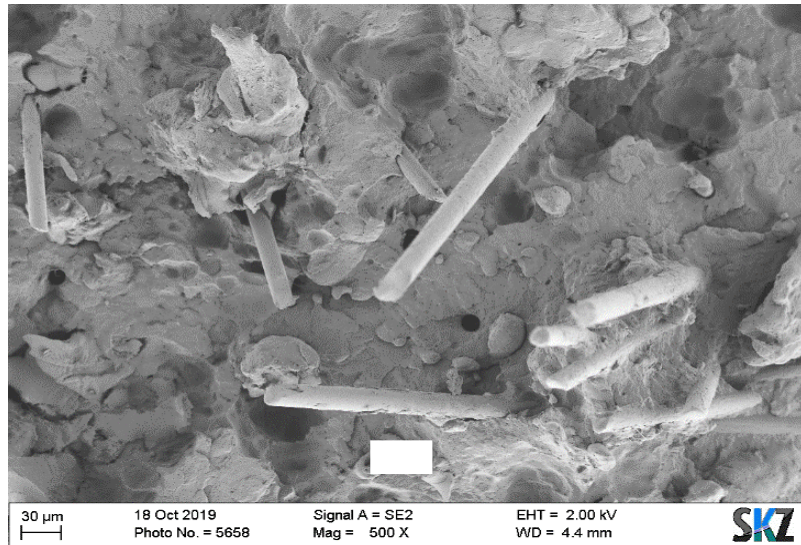


Figure 20. SEM photograph with a 500x magnitude of the breaking area of a 50/50 (PP/UHMWPE) sample with 5% glass fiber and 5% compatibilizer which was impact strength tested.

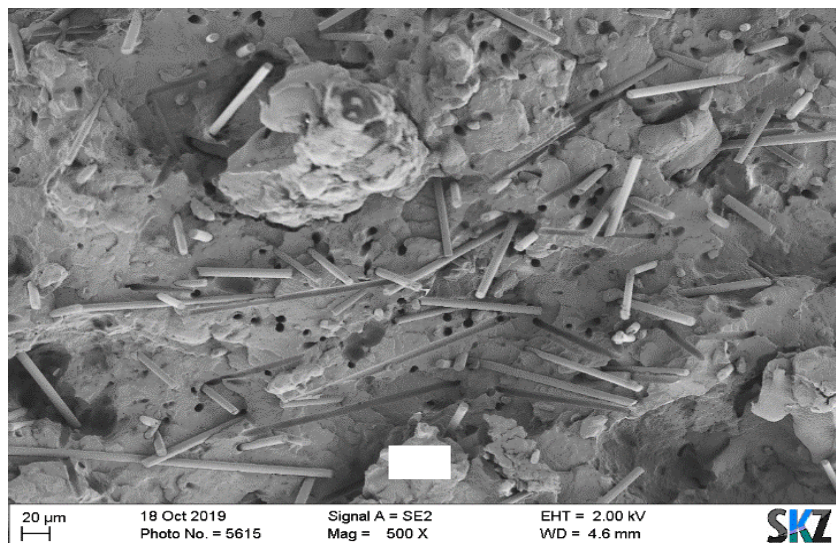


Figure 21. SEM photograph with a 500x magnitude of the breaking area of a 50/50 (PP/UHMWPE) sample with 5% carbon fiber which was impact strength tested.

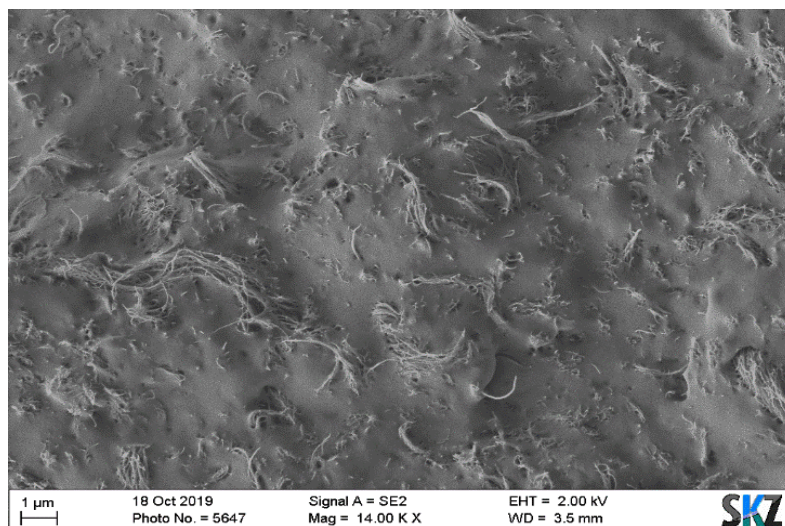


Figure22. SEM photograph with a 14000x magnitude of the breaking area of a 50/50 (PP/UHMWPE) sample with 5% carbon nano-tubes which was impact strength tested.

CONCLUSION& OUTLOOK

This paper investigates the influence of fillers and reinforcement materials on the mechanical and rheological behavior of PP/UHMWPE compounds.

We could show that it is possible to improve the properties of PP/UHMWPE compounds in a significant way by adding fillers and fibers. Adding 5% of various fillers or fibers influences the shear viscosity especially during low shear rates up to 600s⁻¹ and has a big influence on the extensional viscosity.

The used compatibilizer did not show the expected reinforcing effect of mechanical values for tensile and impact testing for PP/UHMWPE compounds. The elongation at break and notched impact stress of all samples dropped rapidly for the samples compounded with compatibilizer.

The used compatibilizer showed no big influence on the E-Modulus and tensile stress of the tested samples. Based on the results of this investigation and our works in the past we will go ahead and research the improvement of the compound properties by adding fillers and fibers.

The upscale to higher capacities using a higher filling level or even a larger screw diameter will be worth to have a look on to be able to produce the compounds in an economic way. Finally, the production of pipes out of the PP/UHMWPE compounds will also be a target for the next months.

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