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# ANALYSIS OF THE PROPERTIES OF IMMISCIBLE POLYMER BLENDS AND THEIR SEPARATION IN A MELTED STATE

## Thesis booklet

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*The referees' opinion of the PhD dissertation and the minutes of the defense meeting can be inspected at the Dean's office of the Faculty of Mechanical Engineering of the Budapest University of Technology and Economics*

# 1. INTRODUCTION

The presence of polymers is increasingly important in everyday life. Plastics can be found in almost all industrial segments: in the area of transport, at work or home environment, as well as in everyday household objects. Mixing of at least two polymers results in a polymer blend, in which a heterogeneous structure forms usually. Blending two or more immiscible polymers is an effective method to achieve novel polymeric materials, where tailoring the properties of the plastics can give a wide range of physical and mechanical properties for the end-use utilization. Therefore, the interest of industrial and academic area is growing for polymer blends. Developing polymer blends also promotes polymer waste recycling, which is necessary because of social pressure and environmental aspects by the European Union at the highest possible level. Currently, there is no uniform approach for polymer recovery. Two methods are widespread: co-processing the recycled plastic waste with suitable chemical additives; or the separation of polymers from the waste stream to neat fractions.

The developing morphology in immiscible binary polymer blends can be classified into disperse/matrix or co-continuous structures (Fig. 1), where the maximum co-continuity of the blends means the concentration of phase inversion. However, most polymers are not compatible with each other, thus a suitable copolymer or a compatibilizer that contains functional groups to establish interactions with the phases is needed to achieve good miscibility between the phases. This addition resulted in finer blend morphology as well as improved physical and mechanical properties.

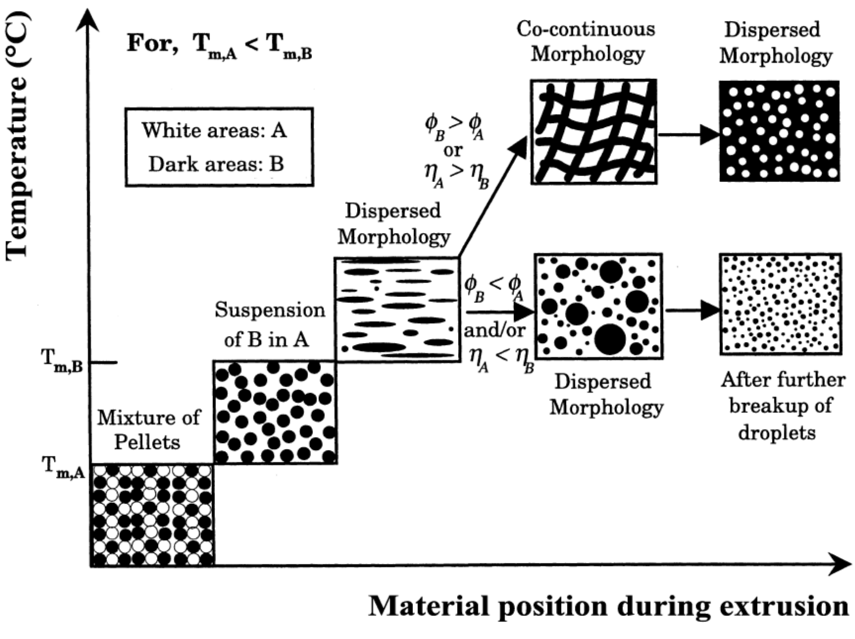



**Figure 1. Forming morphology in case of polymers with two different melting point**

The composition ratio, the dispersed phase size and its size distribution, the viscosity-ratio, the molecular weight, the interfacial and shear stress and the chosen processing parameters have a great influence on the forming morphology of immiscible polymer blends. In addition, the resulting phase structure has a decisive influence on the physical and mechanical properties of polymer blends, for example the toughness during dynamical loads, elongation at break and stiffness during tensile test, and also on flammability. Therefore, it is crucial to explore the mechanisms that occur during processing in order to control the forming morphology to achieve the best physical- and mechanical properties in immiscible polymer blends.

Separation of the mixed polymers to neat fractions is another possibility in case of recycling. It would be desirable if sorting the polymers from the waste stream could be realized in just one step with the required purity, however this is not possible with the most commonly used separation methods in the industry. The reason for this is that polymers are considered clean and homogenous only in the rarest cases in waste stream, because plastics are often associated with other substances, like other polymers, fillers, reinforcement and other chemical additives. Nevertheless, in this case not only the properties will vary but the separation becomes more difficult.

The two different recovery methods were examined in a wide range in my PhD thesis. In this context the goal was to develop polymer blends whose components can be separated from each other at a high purity level, giving an opportunity for value-added recycling later; or to which adding chemical additives resulted in better adhesion between the phases to achieve better properties of blends or longer product life cycle. Further aim was to develop a novel separation method in order to separate the thermoplastics from each other with high purity in just one step, offering new solution for the current separation problems. In parallel with the developed equipment a novel evaluation process was established which provides a quick and clear answer regarding the adequacy of compatibilizers and determines how much additive has to be added to polymer blends. These developments can promote the spread of the theory “cradle-to-cradle” against the “cradle-to-grave” approach.

## 2. SUMMARY OF LITERATURE AND AIMS OF DISSERTATION

The aim of the literature review was to present the effects of morphology on other properties of immiscible polymer blends depending on co-continuous or dispersed phase with different shapes formed. The effects of the emerging phase on the physical and mechanical properties had been investigated in several cases, nevertheless only a small number of research can be found, where the effects of composition ratio, the viscosity ratio and the presence of compatibilizer are investigated at the same time. Previous studies have shown the significant effect of phase inversion, so the impacts of morphology change on other properties had not been examined previously, like mould-shrinkage or burning properties of blends has been examined in details in this PhD thesis. Research carried out by Omonov et al. can give a good basis for determining the phase inversion in polymer blends in an indirect way. It is equally important to know the effects of processing parameters from which the forming morphology, thereby the mechanical properties of the blends significantly depends.

Because of sustainable development it is necessary to deal with polymer mixtures, which are produced for packaging, retail or industrial purposes and after their life cycle become waste. The currently used separation devices are not able to enrich the polymer fragments with high efficiency in one step. With the separation equipment, which is based on the density difference of polymers only one separation boarder can be used at the same time. Thus, in case of waste stream, in which different plastics can be found, further separation steps may be required. Products, in which different polymers previously have been homogenizated in melted state during the compoundation are an unresolved problem, because the components can not be recovered purely, furthermore the density of blend varies depending on the composition ratio. Therefore, after the separation process polymer blends will appear as contaminants in another polymer fraction. Foaming products also introduce reinforcements or fillers for polymers which causes similar problems in density-based classification. Researches, which deal with the separation of plastics, mostly presented the efficiency of the separating method through only two or three different primary plastics. However, these numbers do not cover the real plastic waste stream properly. In municipal solid waste more than five different types of polymer can be found, in shredded waste from automotive waste this number can be even more than ten. The current waste detection procedures are based on statistical sampling where the overall composition ratio of the waste is determined by only a few grams of identified material, which can result in incorrect forecast. Furthermore, the contamination and dark colours deteriorate the efficiency of spectroscopic evaluation.

If the separation of plastics to homogeneous fractions is not achievable, adding a suitable compatibilizer can result in satisfactory properties at the point of view of recycling. Although, predicting the adequacy of compatibilizer is time and money consuming and requires significant technical knowledge during the evaluation process.

The main purpose of my research is to develop a polymer mixture in which the forming morphology can be properly estimated and its life cycle can be extended with the proper additives. Also after usage the components can be separated to neat fractions again, in order to recycle them appropriately. Therefore, in my thesis the “cradle-to-cradle” approach is ought to be realized, and the framework-includes the following:

1. The morphology change has been investigated and analyzed in different polymer blends in a wide range of composition ratios in order to the present the effects of the forming structure on other physical and mechanical properties of blends, with specific regard in case of phase inversion.
2. It has been demonstrated how the compositional ratio, the viscosities of the components and further additives affected the phase structure of blends.
3. The objective was to develop a machine with which two or more plastics can be separated to neat fractions again, regardless whether the melt compounding of components were realized or not. Investigating the effects of the separation parameters was also an important aspect.
4. One of my objectives is to estimate the contents of plastic waste stream more accurately with the developed separator from higher amount of investigated materials compared to the current evaluation methods. It is also important that the contamination and the colours of pellets have slighter impact on the result of examinations. Because of the regulations of the European Communities, a special attention is paid to the area of packaging and municipal solid plastic waste, and also to plastic-rich light fractions recovered from car wrecks during shredding.
5. A new evaluation method would be desirable to verify compatibilizers for the industrial field and for research in the area of polymer blends. The aim is to develop a novel method which provides a quick and clear answer regarding the adequacy of compatibilizers and determines the minimum amount of additive that has to be added to polymer blends.

# 3. APPLIED MATERIALS AND EXPERIMENTAL METHODS

## 3.1. Applied materials

Two high density polyethylenes (HDPE) differing in flowability were blended with polyethylene terephthalate (PET) or polystyrene (PS). The investigated materials are among the most widely used low-cost plastics which enter the markets in large quantities therefore their occurrence in plastic waste stream is also significant. The different flowability of HDPEs leads to different viscosity ratio in PET/HDPE and PS/HDPE blends resulting in different physical and mechanical properties, which can be traced with the morphological changes when the ratio of the applied components has been altered. Furthermore, the effects of styrene/ethylene-butylene/styrene copolymer grafted with maleic anhydride (SEBS-g-MA) have been presented on morphology, rheology, mechanical properties and burning behaviour.

The developed separator device utilizes centrifugal force to enrich the fractions in a melted state, where low density polyethylene (LDPE), HDPE, polypropylene (PP), PS, PET and polyamide 6 (PA6) were applied during the separation and the novel evaluation process. The mentioned plastics represent 80% of the total municipal solid waste; in addition the utilization of these plastics is also remarkable in packaging, electronics or automotive fields. The centrifuge as evaluation procedure was applied for predicting the adequacy of SEBS-g-MA compatibilizer in HDPE/PS blends, where the composition ratio was 50/50 vol%. SEBS-g-MA was added to the blends in 9 different content ratios from 0% to 10%. Two other compatibilizers were also investigated in order to verify the adequacy of SEBS-g-MA with the novel method.

## 3.2. Methods and equipment

**Methods of blend preparing**

The extrusion was carried out in a Labtech Scientific LTE 26-44 twin screw extruder (screw diameter 26 mm, L/D ratio 44). Granulation was realised after cooling in water bath, therefore the granules had to be dried in an air drying oven at 80°C for 2 h in order to remove moisture adhered to the surface. The compoundation in case of PET/HDPE blends occurred with a rotation speed of 40 rpm with a steady increasing heating from 250°C to 275°C, while in case of PS/HDPE blends the heating temperature profile was in the range of 230-255°C with a rotational speed of 75 rpm of the screw.

To prepare the injection moulded specimens with a cross section of 10x4 mm (according to ISO 527-2:2012 standard) an Arburg Allrounder Advance 370S 700-290 (screw diameter 30 mm, L/D ratio 23.3) was used. Due to the different flowability of the two HDPEs the same injection flow resulted in different injection pressure. Therefore, it was necessary to apply different holding pressure profile. Nevertheless, in same type of HDPE-based blends with different PET content the applied injection moulding parameters were the same. The nozzle temperature was always equal to the die temperature of the extruder.

**Methods for investigating the morphological changes in blends**

JEOL JSM 6380LA scanning electron microscopy (SEM) was used at an acceleration voltage of 15-20 kV in secondary electron imaging mode, to study the morphological structures of the cold coated cryogenic fractured surface of blends. The distance of the subject was 8-12 mm.

The longitudinal shrinkage of the injection moulded specimens in a function of time were measured 1 minute, 1 hour, 1 day and 1 week after production with 6 repetitions. The nominal length of the mould cavity was 172 mm.

**Methods for investigating the rheology properties of the plastics and their blends**

According to ISO 1133-1:2011 standard CEAST Modular Melt Flow Model 7027.000 (9 mm piston diameter, 8 mm capillary length, 2.095 mm diameter capillary) was used to measure the melt flow rate, where the applied weight was 2.16 kg and the same temperature was used as for blending. At least 3 repetitions were done for each composition. The melt flow rate of blends containing compatibilizer was measured with the same parameters.

Viscosities of PET, PS and HDPE were recorded in a range of shear rate from 0.01 $s^{-1}$ to 100 $s^{-1}$ using an AR2000 rheometer (TA Instruments) in plate-plate configuration. The measurements started after specimens were held at a temperature of 275°C for PET and 255°C for PS for 5 minutes. The curves of shear rate - viscosity of HDPE have been plotted in both temperatures.

**Determination of the mechanical properties**

Tensile tests were performed on a Zwick Z020 Tester (test speed 20 mm/min, clamping distance 100 mm) at room temperature, and were repeated 5 times for each composition. The cross section of the injection moulded specimens was 10x4 mm, according to standard ISO 527. The movement of the crosshead and the developing force has been recorded by software. From the results the strain, the tensile strength and Young’s modulus were calculated according to conditions and contexts of ISO 527-1:2012 standard.

Charpy impact tests were carried out in a Ceast Resil Impactor Junior impact test machine (15 J hammer, impact rate 3.4 m/s, distance between supports 62 mm), and were repeated 6 times for each composition of the unnotched samples, the size of which were 80x10x4 mm according to ISO 179-1:2010 standard.

**Methods for determining the thermal and burning properties**

According to ISO 4589-2:2000 standard the limiting oxygen index (LOI) was measured in nitrogen/oxygen gas mixture on 10x4x80 mm specimens. Increasing the amount of oxygen in the gas field the limiting oxygen index has been determined when the burning took more than 3 minutes first or the burning length was higher than 50 mm in case of the adjusted gas mixture. The accuracy of the test was ±0.5.

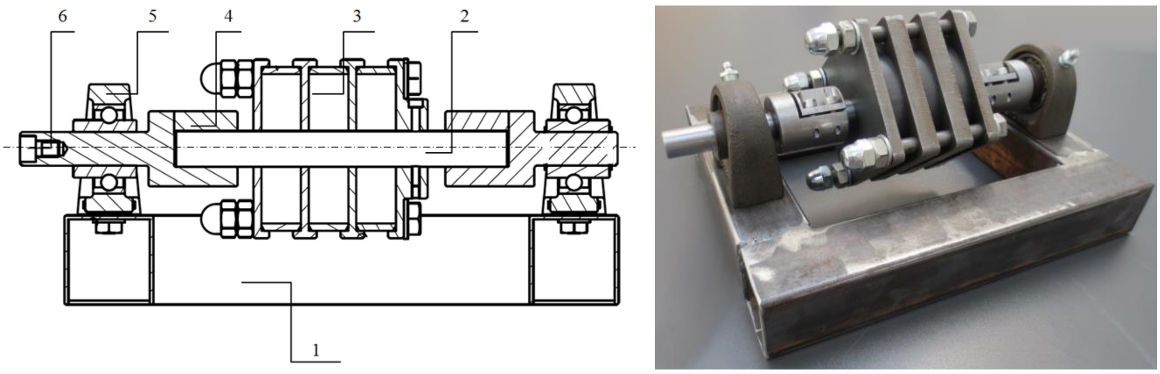
The linear burning rate of samples in horizontal arrangement was calculated by the conditions as declared in UL-94 tests for flammability of plastics. Each specimen was marked with two lines perpendicular to the longitudinal axis of the bar, 25 mm and 100 mm from the end, and the linear burning rate was calculated from the ignited 75 mm length divided by the measured time. The test procedure was conducted on at least three specimens. In case of neat PET samples if combustion passed the first 25 mm mark but did not pass the 100 mm mark, the burning rate of PET was calculated from the elapsed time in seconds and the damaged length.

The heat release rate of PET and HDPE, containing SEBS-g-MA or not, were calculated from compressed sheet with geometry of 100x100x4 mm according to ISO 13927:2015 cone calorimetry standard (heat flux 50 kW/m², voltage ignition). The sheet compressing process was carried out in Collin Teach-Line Platen Press 200E hot press machine with a pressure of 150 bar (in case of the HDPE the pressing realized at 210°C, while 275°C was applied in case of PET; the value of pressure was continuous increased interrupted by aeration).

Thermogravimetric analysis (TGA) was performed on TA Instruments TGA Q5000 IR at a heat rate of 10°C/min, where 6 to 10 mg of samples were examined under flowing nitrogen or air (50 ml/min) over a temperature range from 30°C to 600°C in order to determine the thermal decomposition of the plastics. The characteristic temperature values were determined from the diagram of residue mass as a function of temperature by the points of 1%, 2% and 5% mass loss and also where the temperature value where the derivative curve had a maximum. Another series of measurements were carried out, where the samples were hold for 60 min at constant temperature under flowing nitrogen or air, after an intense heating up by 50°C/min from 30°C. These tests were intended to measure the degradation rate of plastics which occurs in a melted state during the separation.

**Introduction of the developed centrifugal separating machine and description of the evaluation methodology**

To solve the current separation problems a new separation machine was designed and constructed, where the separation of the plastics occurs in their melted state utilizing centrifugal force. Fig. 2. shows the constructed horizontal centrifuge for plastic separation.




**(a)** **(b)**

**Figure 2. (a) schematic overview of the machine /1/ welded frame, /2/ shaft of 18 mm diameter, /3/ three separation tanks of 79.3 mm inner diameter, /4/ soluble coupling, /5/ heat-resistant bearings with housing, /6/ connection to AC motor; (b) constructed horizontal separator**

The shape fixing of separation results was implemented at room temperature with a maintained rotation. The rotation speed of the device, which was 2850±20 1/min, was determined by laser reflection during the operation. The centrifugal force has the greatest impact on separation success due to the awakening forces at spinning. Eq. (1) shows the force which drives the higher density droplet outward to the denser melt lane in radial direction. The separation force depends on the density of the particle and the applied spinning speed.

$$F_{cf} = m \cdot a_{cf} = m \cdot r \cdot \omega^2 = \rho_a \cdot V_a \cdot r \cdot (2 \cdot \pi \cdot n/60)^2 \qquad (1)$$

where $F_{cf}$ is the centrifugal force, which promotes the migration of droplet because of density difference; $a_{cf}$ is the centripetal acceleration; $m$ is the weight of the particle which angular velocity is $\omega$ in rotary inertial frame; $r$ is the distance between the axis of rotation and the particle; $n$ is the rotational speed of equipment in rpm; $\rho_a$ and $V_a$ are the density and the volume of particle $a$.

The surface of melt picks up the shape of the separating tank and forms into a coaxial cylinder shape after the initial period because of the rotation. The components of blends can be separated again to neat fractions at the appropriate test temperature because centrifugal force acts differently on the phases which differ in density. Owing to the influence of centrifugal force, the melted droplets which can be characterized with higher density can migrate towards the wall of separation tank; therefore the lower density phases accumulate near the shaft during the spinning.

## 4. NEW SCIENTIFIC RESULTS

Based on the results achieved on the framework of this PhD dissertation, the following theses have been deduced:

**1st thesis.**

The range of phase inversion of an immiscible polymer blend can be detected indirectly with measuring the mould-shrinkage of injection moulded specimens or determining the limiting oxygen index of blends. Increasing the volume ratio of the phase characzerized by smaller shrinkage increasingly reduces the shrinkage of blends, when its located as dispersed phase in the continuous component with greater shrinkage. In contrast, when the component with greater shrinkage is the dispersed phase has no effect on the shrinkage of blend and the values of the shrinkage depends only from the continuous phase due to the weak adhesion between the phases. The less flammable component has no influence on the limiting oxygen index until it is located as dispersed phase in the more flammable matrix structure. The claim was justified by the results of PET/HDPE and PS/HDPE blends with two different viscosity ratios [1-4].

**2nd thesis.**

The presence of compatibilizer has significant influence not only on mechanical properties but also on the burning characteristics of immiscible polymer blends. Adding 4 vol% of SEBS-g-MA to PET/HDPE blends resulted in at least two times higher elongation and at least 40% higher Charpy impact strength because of improved adhesion between the phases comparing blends with the same composition ratio without additive. At the same time the compatibilizer reduces the tensile moduli of blends in the whole range of the measurement; furthermore the resistance to burning decreases in PET/HDPE blends, when morphology was co-continuous or dispersed structure where the matrix is constituted by the less flammable PET. Due to the highly flammable SEBS-g-MA additive forms combustion hotspots in the continuous PET phase leads to the burning rate of these blends significant increase at 99% confidence level as it decrease the values of limiting oxygen index. The claim was supported by the results of PET/HDPE blends with different viscosity ratio [1-5].

**3rd thesis.**

Two or more immiscible polymers can be separated from each other at high purity and the composition ratio of the identified polymers can be analyzed with a novel density difference-based principle, where the enrichment process occurred in a melted state of the polymers utilizing centrifugal force. For the successful separation at least 0,05 g/cm$^3$ density difference is necessarry between the phases measured by the applied separation temperature in melt state and the proportion of component can vary from 5 to 95 vol% in the mixture [6-10].

**4th thesis.**

The microstructure of blends, where the phases were previously homogenizated by compundation can be decomposed without using chemical solvents with the developed centrifuge separator, in which the separation occurred in a melted state of the polymers. Thus, the components of blends can be separated again to neat, homogenouos fractions. The separaton of immiscible polymers in a melted state utilizing centrifugal force depends not only on the density difference between the phases but also on droplet size. Since the compoundation resulted in smaller droplets in diameter than dry-blended mixtures, on which lower centrifugal force acts. Consequently, more energy investment is needed to separate polymer blends which can be ensured by lower viscosity increasing the separation temperature or longer rotation time by the same rotational speed [9,10].

**5th thesis.**

With the novel evaluation method based on separation, where the blends are investigated in melted state utilizing centrifugal force can be suitable for predicting the adequacy of compatibilizer in polymer blends and to estimate the minimum required amount of compatibilizer, which causes a significant change in the property of blend. The statement can be justified with 2 vol% presence of SEBS-g-MA in PS/HDPE blend with the compostion ratio of 50/50 vol%, at which content the compatibilizer prevented the separation of PS and HDPE phases from each other. It has been proven that the results of the novel evaluation method based on separation are in good agreement with the results of the mechanical tests, where the tensile and impact tests collectively showed that in the above mentioned 2 vol% SEBS-g-MA composition the compatibilizer begins to cause measurable changes in the behaviour of blends [11,12].

## 5. PRACTICAL UTILIZATION OF THE RESULTS

The detailed investigation supports the developments of polymer blends and can promote the recycling of plastics. The burning results are usable in electronics and automotive fields, where the burning properties of plastics can not be ignored. The flammability of blends can be related with the composition ratio of the blend. The negative effect of the presence of compatibilizer in immiscible PET/HDPE blends has also been demonstrated.

With the developed separator it has been presented that two or more polymers can be separated from each other at high purity level within a short time giving a chance for value-added recycling later. More than one separation border can be developed based on the properties of plastics supporting the further analysis of the composition ratio. With the centrifuge it was firstly presented on components which were previously compounded to blends that they can be separated to neat fractions again without chemical solvents, which allows the separation of components of multi-layer packages and multicomponent engineering products (Fig. 3.). Separation in a melted state as evaluation method can be suitable for predicting the adequacy of additives in polymer blends.

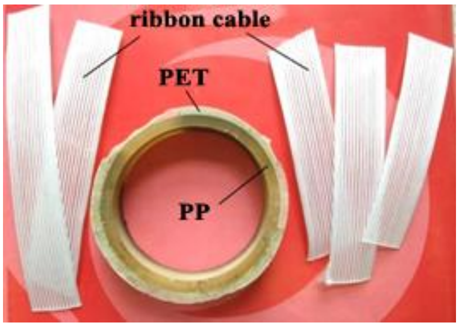



**Figure 3. Separation of PET/PP ribbon cable to homogeneous fraction (received from 3B Hungária Ltd.)**

From 2015 the end-of-life vehicle wrecks must be recycled in 95%. Hence, it is necessary to deal with the plastic-rich light fractions during the recycling. With the separation results of my PhD thesis and with the well-chosen additives and production methods it has been proven that from the recovered plastics from automotive waste a new engineering product can be created again (Fig. 4.).

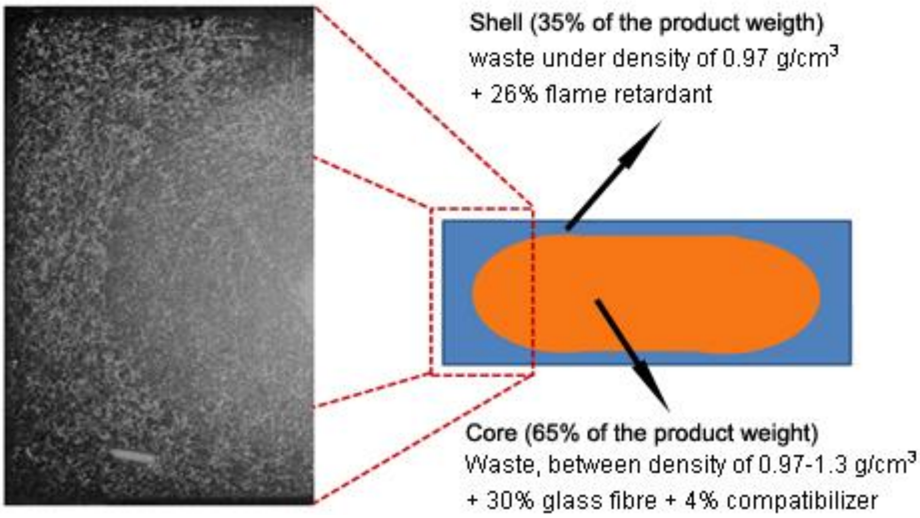



**Figure 4. Morphological structure of automotive internal door opener arm produced by two component injection mouldings and the value-added recycling possibilities adding reinforcement, flame retardants and compatibilizer to the separated fraction**

# 6. LIST OF PUBLICATIONS

## List of own publications related to thesis


[ 1 ] **Dobrovszky K.**, Ronkay F.: Effects of phase inversion on mold shrinkage, mechanical and burning properties of injection molded PET/HDPE and PS/HDPE polymer blends. Polymer-Plastics Technology and Engineering, **submitted** (2016). *IF=1,511*

[ 2 ] **Dobrovszky K.**, Ronkay F.: Influence of the phase inversion on mould-shrinkage, mechanical- and burning properties of polymer blend. Materials Science Forum, **in press** (2016).

[ 3 ] **Dobrovszky K.**, Ronkay F.: Effects of SEBS-g-MA on rheology, morphology and mechanical properties of PET/HDPE blends. International Polymer Processing **30**, 91-99 (2015). *IF=0,523*

[ 4 ] **Dobrovszky K.**, Ronkay F.: Influence of morphology and compatibilizer on burning behavior of PET/HDPE blend. AIP Conference Proceedings, **in press** (2016).

[ 5 ] **Dobrovszky K.**, Ronkay F.: Toughness improvement in ternary HDPE/PS/PET polymer blends with compatibilizer. Acta Technica Jaurinensis **8**, 36-46 (2015).

[ 6 ] **Dobrovszky K.**, Ronkay F.: Polimerek újfajta szétválasztási lehetősége. Mechanoplast 2013 (Ed.: György Czél), Miskolc, 2013, 1-6. ISBN: 978-963-358-033-2.

[ 7 ] **Dobrovszky K.**, Csergő V., Ronkay F.: Alternative, new method for predicting polymer waste stream contents. Materials Science Forum **812**, 247-252 (2015).

[ 8 ] **Dobrovszky K.**, Ronkay F.: Új fegyver a műanyaghulladékok ellen: magyar felfedezés segítheti az újrahasznosítás problémáit. Élet és Tudomány, **in press** (2016).

[ 9 ] **Dobrovszky K.**, Szabó D.K., Ronkay F.: Műanyag keverékek ömledékállapotban történő szétválaszthatóságának vizsgálata. Polimerek **1**, 155-160 (2015).

[ 10 ] **Dobrovszky K.**, Ronkay F.: Alternative polymer separation technology by centrifugal force in a melted state. Waste Management **34**, 2104-2112 (2014). *IF=3,220*

[ 11 ] **Dobrovszky K.**, Budinszki B., Ronkay F.: Kompatibilizálószer hatása PS/HDPE polimer keverék reológiai, morfológiai és mechanikai tulajdonságaira. Gradus **3**, 11-22 (2016).

[ 12 ] **Dobrovszky K.**, Ronkay F.: Investigation of compatibilization effects of SEBS-g-MA on polystyrene/ polyethylene blend with a novel separation method in a melted state. Polymer Bulletin **73**, 2719–2739 (2016). *$IF_{2015}$=1,371*

**List of other publications related to PhD studies**

[ 13 ] Ronkay F., **Dobrovszky K.**, Toldy A.: Műanyagok újrahasznosítása. Budapest University of Technology and Economics, Budapest, 2015.

[ 14 ] **Dobrovszky K.**, Ronkay F.: SEBS-g-MA adalékanyag hatása PET/HDPE keverékek tulajdonságaira. X. Országos Anyagtudományi Konferencia, Balatonalmádi, 2015. október 11-13. (poster)

[ 15 ] **Dobrovszky K.**, Ronkay F.: Effects of compatibilizer on morphological, rheological and mechanical properties of polymer blend. Polymer Processing Society Conference 2015, Graz, 2015. szeptember 21-25. (oral presentation)

[ 16 ] **Dobrovszky K.**, Ronkay F.: Új módszer kidolgozása autóipari műanyag hulladékáram összetételének előrejelzésére. IX. Országos Anyagtudományi Konferencia, Balatonkenese, 2013. október 13-15. (poster)

[ 17 ] **Dobrovszky K.**: Műanyagok sorsa a hulladékba kerülés után. IX. Szent-Györgyi Albert Konferencia, Budapest, 2015. április 11. (oral presentation)

[ 18 ] **Dobrovszky K.**: Upcycling of polymer waste from automotive industry. Periodica Polytechnica Mechanical Engineering **55**, 73-77 (2011).

[ 19 ] **Dobrovszky K.**, Ronkay F.: Minőségnövelt hulladékhasznosítás kétkomponensű fröccsöntés alkalmazásával. Műanyag és Gumi **49**, 48-51 (2012).

[ 20] **Dobrovszky K.**: Upcycling of polymer waste from automotive industry. Gépészet 2012: Proceedings of the eighth international conference on mechanical engineering (Ed.: Gábor Stépán). Budapest, Magyarország, 2012, 83-89. ISBN: 978-963-313-055-1.