Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

19: 1 (2019) 30-33

COMPOSITES THEORY AND PRACTICE
ISSN: 2084-6096
ISSN (online): 2299-128X

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Received (Otrzymano) 30.02.2019

THE USE OF SHREDDED CAR WINDSCREEN WASTE AS REINFORCEMENT OF THERMOPLASTIC COMPOSITES FOR 3D (FDM) PRINTING

The work presents preliminary attempts to create a filament for 3D printing (FDM technique) based on a low density polyethylene (LDPE) composite reinforced with shredded windscreen glass. The glass powder was obtained by grinding windscreen glass wastes. PVB (polyvinyl butyral), which is an integral part of safety glass car windscreens, was not removed from the obtained powder. The obtained powder had a range of grain diameters 90÷160 μm. The powder was then mixed mechanically and in an ultrasonic chamber with LDPE granulate. The composites were made by extrusion with one regranulation cycle. The filament for FDM printing was produced by extrusion winding with cooling in open air. A filament with a diameter of 1.45±0.05 mm was obtained. The produced filaments were subjected to a static tension test and SHORE hardness tests. In order to compare the material, the maximum stress recorded at 50% elongation was determined for each tested material. It was observed that along with the increase in the glass content, the strength of the filament decreased slightly. The basic stage in evaluation of the produced materials was to carry out trial prints on an FDM printer. The printing temperature was selected experimentally during a series of trials. The best results were obtained at the print temperature of 250°C and table temperature of 90°C. During printing, an unfavorable effect of filament bending was observed in the printer, below the supplying roller. This effect occurred during printing at a supply speed of more than 1 mm/s. Special additional printing tests with supply rates below 1 mm/s were carried out. This made the printing possible, and it showed the evident superiority of the composites over the neat LDPE. The problem with the stability of filament supply during printing was partially solved by mechanical stiffening of the line between the rollers, using specially printed inserts. The trial prints made from the tested composites occurred to be of better quality than those from the neat LDPE. They show less deformation caused by shrinkage. These effects result from stiffening of the material caused by the addition of hard glass particles. It was found that an addition of a minimum of 30% of the glass particles is required to have a significant effect on the LDPE stiffness.

Keywords: **3D printing, FDM technique, low density polyethylene, car windscreen glass, recycling**

WYKORZYSTANIE ROZDROBNIONYCH ODPADÓW SZYB SAMOCHODOWYCH JAKO WZMOCNIENIA KOMPOZYTÓW TERMOPLASTYCZNYCH PRZEZNACZONYCH DO DRUKU 3D (FDM)

Przedstawiono wstępne próby wytworzenia filamentu do druku FDM na bazie kompozytu LDPE wzmocnionego rozdrobnionym szkłem z szyb samochodowych. Osnową badanych kompozytów był polietylen niskiej gęstości (LDPE). Jako wzmocnienie zastosowano proszek szklany uzyskany poprzez zmielenie stłuczki z windscreen-glass. Z uzyskanego proszku nie usuwano foli PVB, która jest integralną częścią bezpiecznych car windscreens. Uzyskany proszek miał zakres średnic ziaren 90÷160 μm. Proszek został następnie zmieszany z granulatem LDPE, mechanicznie oraz w komorze ultradźwiękowej. Kompozyty wytworzono metodą wytłaczania z jednorazową regranulacją. Filament do druku FDM wytwarzano metodą wytłaczania-nawijania z chłodzeniem na wolnym powietrzu. Uzyskano filament o średnicy 1,45±0,05 mm. Wytworzone filamenty zostały poddane próbie statycznego rozciągania oraz próbom twardości metodą Shore'a. W celu porównania materiału wyznaczano maksymalne naprężenia zarejestrowane przy wydłużeniu 50%. Zaobserwowano, że wraz ze wzrostem udziału szkła spada nieznacznie wytrzymałość filamentu. Zasadniczym etapem oceny wytworzonych materiałów było przeprowadzenie próbnych wydruków na drukarce FDM. Temperaturę drukowania dobierano eksperymentalnie w ramach serii prób. Najlepsze efekty uzyskano przy temperaturze druku 250°C i temperaturze stołu 90°C. W trakcie drukowania zaobserwowano niekorzystny efekt wyginania się filamentu w drukarce, poniżej rolki podającej. Efekt ten występował przy drukowaniu z prędkością podawania większą niż 1 mm/s. Zastosowano specjalne dodatkowe próby drukowania z prędkością podawania poniżej 1 mm/s. Umożliwiło to druk, przy czym wykazało ewidentną wyższość kompozytów nad nite LDPE. Problem ze stabilnością podawania filamentu podczas drukowania został częściowo rozwiązany poprzez mechaniczne usztywnienie żyłki między rolkami za pomocą specjalnie wydrukowanych wkładek. Wydruki próbne uzyskane dla badanych kompozytów są lepsze jakościowo niż dla nite. Wykazują mniejszą deformację wywołaną skurczem. Te efekty wynikają z usztywnienia materiału spowodowanego dodatkiem twardych cząstek szkła. Stwierdzono, że znaczący wpływ na sztywność LDPE wymaga zastosowania minimum 30% dodatku cząstek szkła.

Słowa kluczowe: **druk 3D, technika FDM, polietylen niskiej gęstości, szkło z szyb samochodowych, recykling**

INTRODUCTION

The industrial recycling of laminated glass from car windscreens primarily involves the processing of glass cullet: chemical, thermal or mechanical removal of polyvinyl butyral (PVB) and remelting in a glassworks [1, 2]. This is an expensive procedure and - depending on the local conditions - has limited applicability. The methods of processing waste glass into ceramic granulates [3] or as a raw material to produce silicon carbide (SiC) [4] have also been described. However, they are experimental or low-scale methods. The issue of car glass waste management is still open and a significant part of this material is simply landfilled. This means there is a permanent need to find ways to manage it. One of the potential solutions is an attempt to use appropriately shredded car glass to strengthen filaments for 3D printing.

FDM (filament deposit modeling) is a dynamically developing rapid prototyping technology - widely described, e.g. in [5]. The materials popular in this technique include PLA, ABS and PEEK. This technology is so young that not too many studies on the possible management of waste materials in it have been conducted. Few descriptions indicate the use of primary material waste - PLA or ABS, or alternative materials such as PS or HDPE [6, 7]. In addition, the production of thermoplastic composites with ceramic reinforcement is described in [8]. Nonetheless, no attempts have been made to produce filaments from low density polyethylene (LDPE), or composites with glass powder filling. Why LDPE? Because it is probably the most popular, and at the same time the cheapest, polymer material. It is characterized by high chemical resistance and flexibility, which would predestine it for the production of specific groups of printed products, e.g. gaskets or machine elements. Theoretically, elements of reinforcing structures for layered composites can also be used - e.g. for modern solutions resistant to impact loads [9, 10]. Yet another application may be the printing of dedicated elements for the repair of old structures of various types, which is also an emerging branch of materials engineering [11]. The problem of LDPE is its low stiffness, which significantly hampers (in practice - disables) the printing process in typical FDM printers and makes the products more sensitive to deformation caused by shrinkage - a characteristic feature of thin layered polymer structures [12]. One of the methods of achieving LDPE stiffening, while maintaining its essential properties and maintaining a reasonable production cost, is to reinforce it with shredded waste windscreen glass.

This paper presents preliminary attempts to produce a filament for FDM printing based on an LDPE composite reinforced with shredded windscreen glass.

MATERIALS AND METHODS

The matrix of the tested composites was LDPE by BRENNTAG, Germany. As the reinforcement, glass powder obtained by grinding windscreen glass cullet was used. Grinding was carried out initially in cross-flared mills and then in a planetary mill. Polyvinyl butyral (PVB) foil, which is an integral part of safety glass car windscreens, was not removed from the ground material. The obtained powder, for the purpose of this preliminary study, was sieved to the range of grain diameters 90÷160 μm (for an assumed print path thickness of 0.2 mm).

After grinding and sieving, the powder was joined together with LDPE granulate, in a weight ratio of about 50/50 and mechanically mixed with subsequent treatment in an ultrasonic chamber (low power) for 20 min. Such a mixture was an essential substrate to produce the composites.

The composites were produced by extrusion using a ZAMAK DTR EHP-2x16S extruder (ZAMAK, Poland) at the screw speed of 28 rpm. The feedstock for the process was LDPE granulate metered alternately with the LDPE + glass powder mixture, in appropriate ratios. The initial analysis of the properties of the obtained material indicated the necessity for its regranulation (fragmentation and second extrusion) in order to make it homogeneous.

The FDM filament was produced by extrusion winding (free air cooling) employing the above-mentioned extruder at the screw speed of 28 rpm and winding speed of 8 rpm. The feedstock for the process was previously prepared granules with the appropriate content of windscreen glass particles (Table 1). The diameter of the obtained filaments was 1.45±0.05 mm.

TABLE 1. **Characteristics of tested materials**
TABELA 1. **Charakterystyka badanych materiałów**

	LDPE weight content	Glass weight content	Hardness Shore D	Rm* [MPa]
LDPE100 (neat)	100%	0%	32 ± 1.2	8.9 ± 0.6
LDPE085	85%	15%	31 ± 0.8	8.5 ± 0.4
LDPE070	70%	30%	39 ± 1.8	8.2 ± 0.5
* equals stress designed at elongation of 50 mm				

The produced filaments were subjected to a static tensile test. The length of the measuring base was 100 mm, the deformation speed was 25 mm/min, and the device used was an INSTRON 4469. The material in each case tended to flow plastically. In order to compare the material, the maximum stress recorded at 50% elongation (Table 1) was determined for each sample. It can be noticed that with the increase in the volume fraction of glass, the strength of the filament decreases slightly and the characteristic yield point visible for the neat LDPE disappears in the case of the composites - Figure 1.

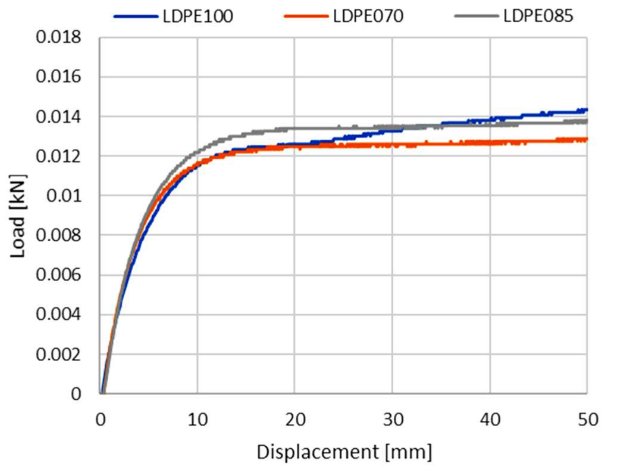

Fig. 1. Representative tensile curves of neat LDPE and of produced composites

Rys. 1. Reprezentatywne krzywe rozciągania czystego LDPE i wytworzonych kompozytów

The final stage of evaluation of the produced materials was to carry out trial prints on a ROBO R1+ printer (ROBO, USA). The printing parameters are presented in Table 2.

TABLE 2. **FDM printing process parameters for produced materials**

TABELA 2. **Parametry procesu drukowania FDM dla wytworzonych materiałów**

Head nozzle diameter	Table temperature	Printing temperature	Path thickness	Rate of printing	Rate of printing for first layer
0.4 mm	90°C	250°C	0.4 mm	10; 5; 2 mm/s	50%

The printing temperature was established experimentally within a series of trials, and the temperature shown in Table 2 gave the best results. No additional cooling was used.

EVALUATION OF OBTAINED RESULTS

As predicted, during printing there was an unfavorable bending effect of the filament in the printer, below the supply roller. This effect occurred in all attempts when printing at a speed of more than 1 mm/s (Fig. 2). Special printing tests were carried out at a supply rate of less than 1 mm/s. The printout of the neat LDPE, despite the low printing speeds, tended to stutter. This was evident during printing of the second layer, when the neat LDPE usually stopped printing. The composites containing fragmented windscreen glass showed some difficulties only at the third or fourth layer. The problem with the stability of filament supply during printing was partly solved by mechanical stiffening of the line between the rollers and the head. Special inserts (previously printed) were used for this purpose - they were modeled on previous experiments [13]. The condition of low printing speeds still has to be met, however, we can effectively print from LDPE and its composites (Fig. 3).

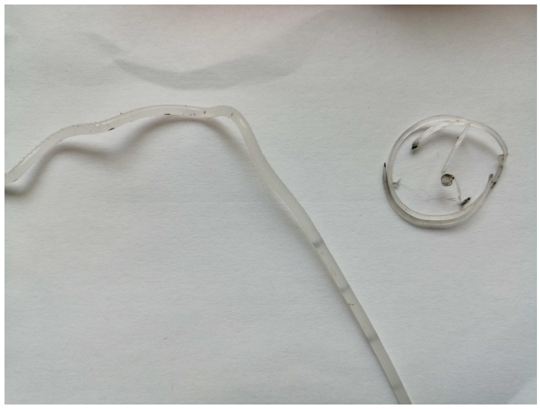

Fig. 2. Behavior of neat LDPE print and filament during printing at rates above 1 mm/s - visibly deformed filament and unsuccessful vestigial printout

Rys. 2. Zachowanie wydruku oraz filamentu z czystego LDPE przy prędkościach powyżej 1 mm/s - widoczny zdeformowany filament i nieudany szczątkowy wydruk

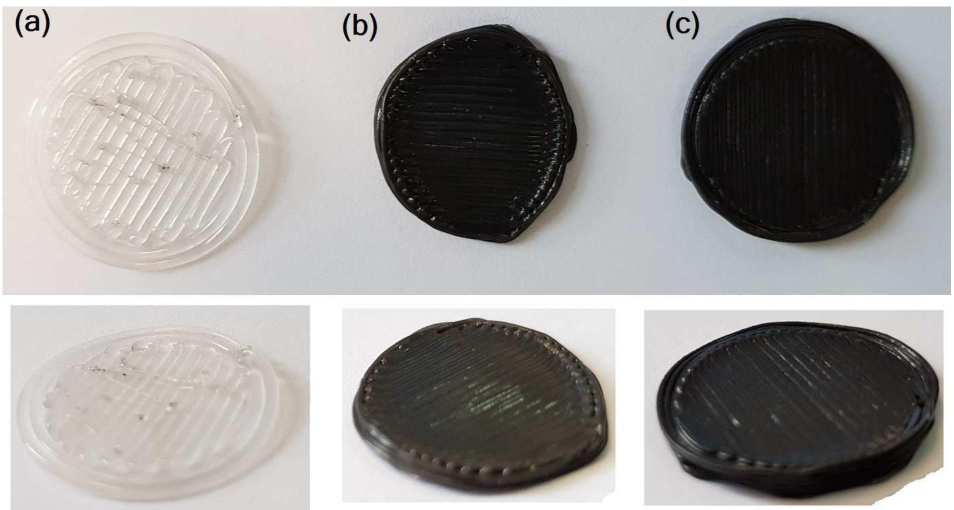

Fig. 3. Printouts obtained at low printing rate from tested materials: a) LDPE100, b) LDPE085, c) LDPE070

Rys. 3. Wydruki uzyskane przy małej prędkości druku dla badanych materiałów: a) LDPE100, b) LDPE085, c) LDPE070

The trial printouts obtained from the LDPE085 and LDPE070 composites are of better quality and more homogeneous than in the case of LDPE100 processed under the same conditions. They also show less deformation due to contraction. These effects result from stiffening of the material caused by the addition of hard glass particles. This is indicated by the increase in hardness visible in the LDPE070 composite compared to the neat LDPE100 (Table 2). There was no proportional increase for LDPE085, which is not obvious, but it indicates the insufficient effect of the particles on the matrix in such a small amount. It is apparent (Fig. 3) that the LDPE085 printout shows some deformation due to shrinkage, whereas the LDPE070 printout virtually does not show it. Therefore, using a minimum of 30% addition of glass particles is required to have a significant effect on the LDPE stiffness. There is no significant impact of the PVB present in the composite materials on their properties or processing - however, it may be found in further, more precise research.

CONCLUSIONS

- LDPE printing using the FDM method is possible, however, it requires low printing speeds and the use of special stiffening (stabilizing) inserts.
- The addition of shredded car windscreen glass slightly (but clearly) improves the behavior of the LDPE filament during the printing process, significantly improves the quality of the obtained printouts, and especially reduces shrinkage during cooling. The amount of 30% by weight of glass should be rather treated as the minimum amount to obtain the desired effects.
- Further work on the use of LDPE in FDM printing should focus on the possibility of accelerating the printing rate by making design changes in printers (larger supply nozzles), or ensuring adequate stiffness of the material itself - e.g. by creating custom blends (with polypropylene or polystyrene) and, obviously, by producing composites with hard components.

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