Recycling of ABS operating elements obtained from industry 3D printing machines

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Abstract: The article presents new application of the material obtained from the recycling of acrylonitrile-butadiene-styrene (ABS) – the material acquired from operating parts of industry Dimension Elite 3D printer by Stratasys. The operating parts were used to prepare the regranulate and to produce filament, the latter of which was applied used in the FFF technology (Fused Filament Fabrication).

Manufactured in the FFF technology, test specimens were used to determine the selected mechanical properties and to compare the obtained results with the properties characteristic of molded pieces made of ABS regranulate that were produced by injection molding. The paper presents results of tests performed on a filament, obtained from the ABS regranulate and indicates characteristic processing properties of that material. It also discusses beneficial processing parameters for injection molding (IM) and 3D printing (FFF). The study also presents selected results of tests of functional properties of ABS products in the FFF technology. The research results have allowed to assess the possibility of recycling of the operating parts of 3D printers in FFF.

Keywords: ABS recycling, filament production, 3D printing, FFF technology, mechanical properties, processing properties.

Recykling części eksploatacyjnych z ABS wykorzystywanych w przemysłowych drukarkach 3D

Streszczenie: Przedstawiono nowe zastosowanie materiału uzyskanego z recyklingu ABS (akrylonitryl-butadien-styren) pochodzącego z elementów eksploatacyjnych przemysłowych drukarek 3D Dimension Elite (Stratasys). Z elementów eksploatacyjnych przygotowano regranulat i wyprodukowano filament, który następnie zastosowano w technologii przyrostowego wytwarzania FFF (ang. *Fused Filament Fabrication*).

Wytworzone w technologii FFF próbki posłużyły do oznaczenia wybranych właściwości mechanicznych oraz porównania ich z właściwościami charakteryzującymi wypraski z regranulatu ABS, uzyskane metodą wtryskiwania. Oceniano cechy filamentu otrzymanego z regranulatu ABS, wskazano także na charakterystyczne właściwości przetwórcze tego surowca. Określono, korzystne pod względem wytrzymałości mechanicznej, parametry procesów wytwarzania: wtryskiwania ciśnieniowego (IM) oraz drukowania 3D (FFF), wyznaczono też właściwości użytkowe wytworów z ABS, otrzymanych w technologii FFF. Wyniki badań pozwoliły na ocenę możliwości recyklingu zużytych elementów eksploatacyjnych przemysłowych drukarek 3D w technologii FFF.

Słowa kluczowe: recykling ABS, wytwarzanie filamentu, drukowanie 3D, technologia FFF, właściwości mechaniczne, właściwości przetwórcze.

Advantageous functional and processing properties of the ABS co-polymer and its combinations make it a material ideal for manufacturing of toys, housings of electronic equipment and the elements of equipment applied in industry. Visible and continuous development of the electronic industry demonstrates itself mainly through the manufacture of new and innovative products. After a short period of use (up to 5 years), most of them lose their functional properties and constitute a waste product. As a consequence, the amount of post-use waste in the E&E industry (Electrical & Electronic), including the used elements of electronic equipment housings, is rapidly rising. Secondary use of material potential of this type of ABS terpolymer products seems to be crucial due to the high cost of primary granules used in the production of electronic equipment [1].

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Additive manufacturing technologies are currently one of the fastest developing methods of manufacturing of prototypes and small batches of products connected with polymer processing [2–4]. The fused filament fabrication (FFF) method, just as the fuse deposition modelling (FDM), use extrudates (the so-called filament) as an input material, which is made of the ABS co-polymer or other polymers [5–7].

Considering the fact that the purchase cost of the filament is currently many times higher than the price of the ABS terpolymer as a granulate, the secondary use of the ABS recyclates from E&E equipment housings to produce the filament is economically justified. This activity is consistent with the most demanded tendency to use raw materials obtained from mechanical recycling to manufacture goods of high market value (up-cycling). It is also beneficial from the point of view of the reduction of CO_2 emissions and the higher importance of the mechanical recycling technology, which is preferred in the EU. By 2020, the stockpiling of polymer waste will have been prohibited in all EU member countries. In some of them (*i.e.* Germany, Austria, and Scandinavian countries), such legislation has already been made effective. In the above mentioned countries the primary goal is to use the material potential of waste (mechanical recycling) by incineration and, secondly, the policy of energy recovery by combustion is practiced [8, 9].

Additive technologies of manufacturing with the use of a polymer filament are studied in terms of, among others, determining mechanical properties, where the impact on the product quality is verified: a) process settings [10–12], b) printing orientation [13–16], c) types of materials used [17–19]. Dimensional accuracy of products based on the standardized samples [20, 21] and control geometries [22–24] is also subject to verification.

The previously conducted studies on the secondary use of materials in additive technologies have been focused on the effective production of spatial objects out of the filament [25–29]. Various design solutions of printing heads of 3D printing machines that lean towards using granulate or regranulate as an input material are taken into consideration as well [30–32]. There are known attempts at managing polymer waste in order to obtain functional filament used in the RepRap devices [33]. The literature gives a great deal of information on the secondary use of ABS recyclates obtained by injection molding mainly. However, there are also known attempts undertaken to process ABS electronic equipment waste into the material enabling its re-use as an input material for the fused filament fabrication [34]. Nevertheless, there is still a lack of reports on the attempts at managing the ABS terpolymer waste obtained from industry 3D printers in order to produce filament. The purpose of the present study is an attempt to use the ABS recyclate for direct manufacturing of the filament with expected and reproducible functional properties. It has been assumed that the quality of a filament from the secondary material is a derivative of mechanical recycling processes performed (especially grinding and re-granulation molding) and it also depends on the grain composition of the recyclate. The study aims at obtaining products with higher quality and dimensional reproducibility in the FFF technology.

EXPERIMENTAL PART

Materials

The study aimed at attempting the secondary use of operating parts derived from 3D printers made of the ABS polymer. The molded pieces subject to mechanical

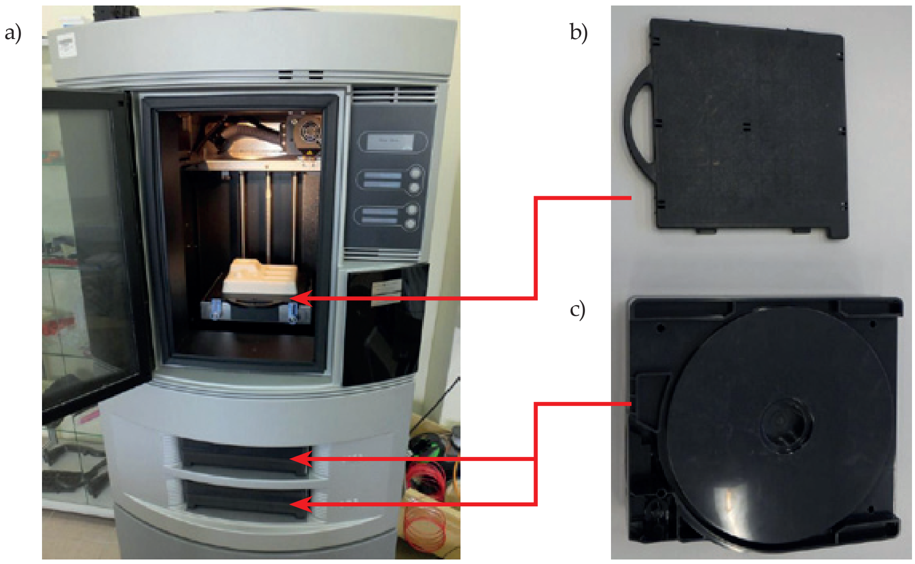

Fig. 1. Operating elements made of ABS copolymer obtained from: a) the Stratasys 3D Dimension Elite industrial printer, b) a worktable, c) a filament storage cassette

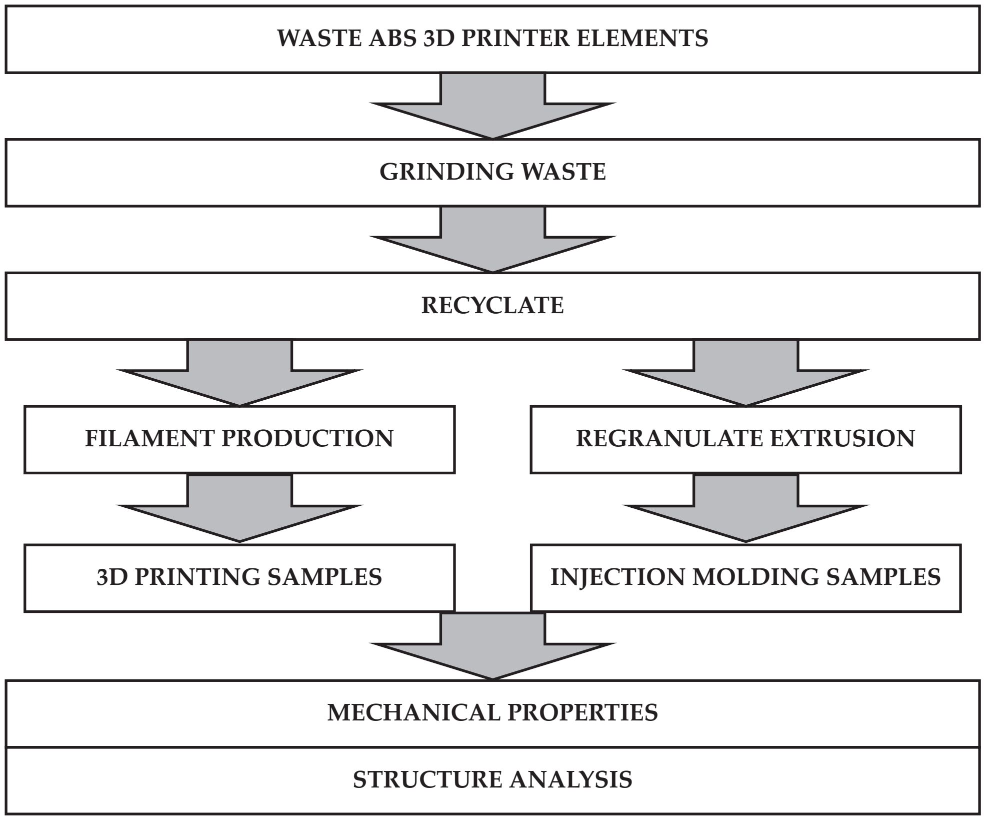

Fig. 2. Stages of mechanical recycling of ABS waste

recycling were selected in terms of their external dimensions, wall thickness, and a flow path length of a melted polymer in primary processing (Fig. 1).

Methodology

The experiment proposed a procedure to allow a complete management of used operational parts through production of a filament in the FFF additive technology (Fig. 2). The operational parts of an average wall thickness of 2.20 ± 0.03 mm were initially cut with a hand-operated workshop guillotine. Subsequently, the material was shredded using a Rapid 2a cutter shredder, where gap between moving and static cutting knives was set to 0.1 mm and a sieve with holes of Ø 8 mm diameter was used.

For the sieve analysis, sieves with the following opening sizes were used: Ø 7 mm, Ø 5 mm, Ø 3.5 mm, and Ø 2 mm. Before being re-processed, the recyclate had been dried in a temperature of 80 °C for four hours in the Binder FED-115 dryer (Germany). Then, using the granulate production line equipped with the W25-30D single-screw extruder manufactured by Metalchem (Poland) and with the cold re-granulation mill manufactured by Metalchem (Poland), the ABS co-polymer regranulate was produced.

The temperature values in the extruder plasticising unit zones were as following: I – 165 °C, II – 180 °C, III – 220 °C; head zone – 220 °C. The extrusion screw worked at a rotation speed of 80 rpm. During the regranulate production, an extrusion head equipped with a nozzle of Ø 3 mm in diameter was used. Before the next extrusion process, the regranulate drying stage was repeated with the same parameters as in the drying of the recyclate.

The recyclate obtained was subject to the sieve analysis in order to determine its grain distribution. Apart from using the ABS regranulate for the manufacture of a filament, some part of the secondary material was used to manufacture test pieces in the injection molding technology on DE 55 injection molding machine by Tederic (China). The following processing parameters were adopted: injection pressure 69.1 MPa, injection velocity 51 mm/s, clamping pressure: 55 MPa, clamping time: 16 s, cooling time: 30 s and dosage path 56 mm. The plasticizing unit zone temperatures of injection molding machine were as follows: I – 40 °C, II – 230 °C, III – 240 °C, IV – 250 °C, V – 241 °C; the hot runner nozzle temperature was 250 °C. For FFF additive technology, the filament obtained was used to manufacture samples with the same geometrical features as the ones of injection molded pieces. The dimensions were consistent with PN-EN ISO 527. The extrusion process velocity was set at 2.63 m/min.

The layered model of FFF specimens was generated with the use of Simplyfy3D ver. 4.1 software (the USA). For the additive manufacturing of test specimens Ultimate Professional tool by Monoprice (the USA) and the following settings applied: nozzle diameter of 0.4 mm, layer height of 0.2 mm, working head temperature of 260 °C, working table temperature of 90 °C, material flow through the nozzle of 140% and the printing velocity of 30 mm/s.

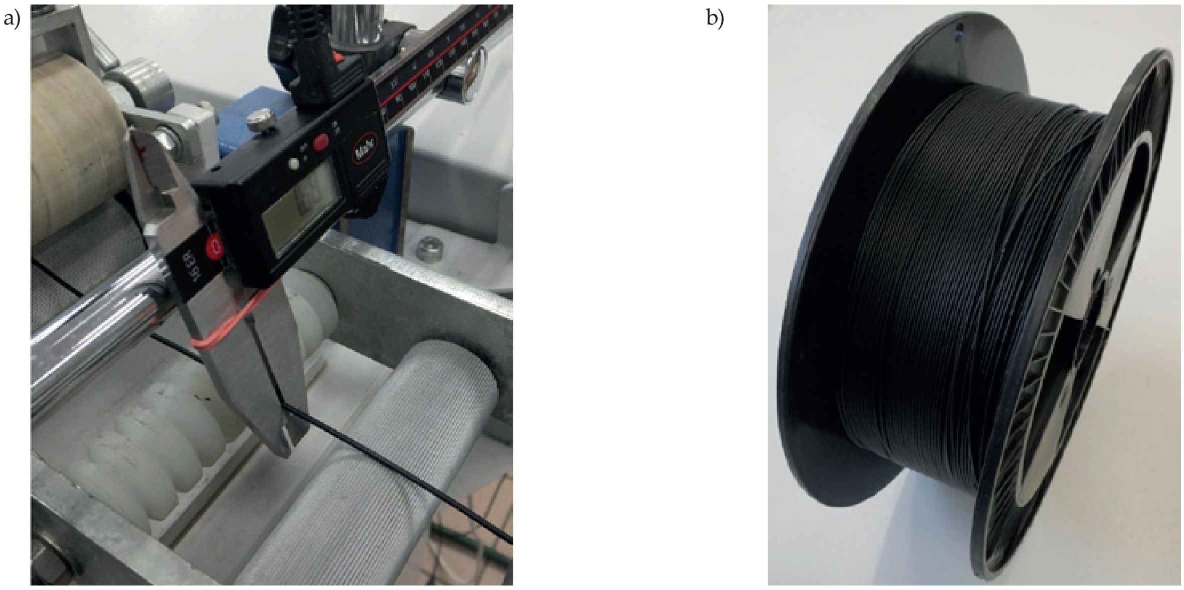

Fig. 3. View of the filament obtained from ABS regranulate: a) on-line measurement of the extrudate diameter during production, b) a finished filament ready to use in the FFF technology

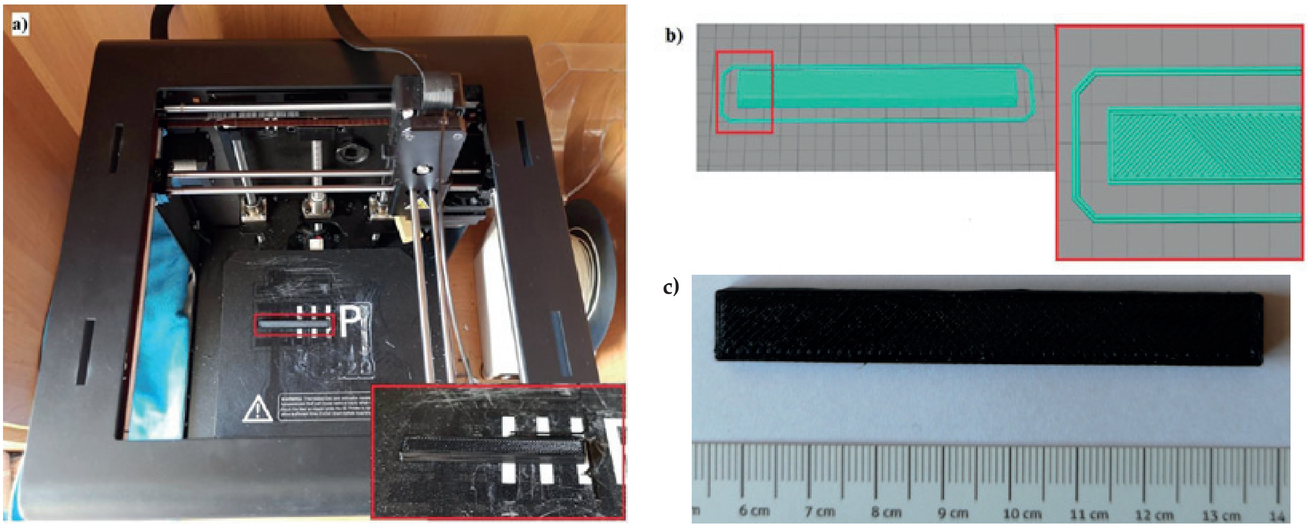

Fig. 4. Additive manufacturing of the samples in the FFF technology: a) Ultimate Professional Printer by Monoprice, b) a method of layering the plastics inside the sample, c) an exemplary FFF sample intended for mechanical tests

Methods of testing

Measurements to verify the diameter of the extrudate obtained were performed on-line with the use of a MarCal 16EWR digital calliper manufactured by Mahr (Germany), as can be seen on Fig. 3. The extrudate diameter was measured on its randomly chosen section every 2 seconds, having obtained results from 500 repeats automatically registered by MarCom Professional software (Germany).

The test of regranulate melt flow index was conducted using an Aflow plastometer manufactured by Zwick/Roell (Germany).

For the impact tests and the three-point static flexural test, samples in a bar-form were applied (Fig. 4). The bars were manufactured by the method of applying consecutive layers as presented on Fig. 4b. The method of maximum filling was chosen. The individual threads of a layer inside a sample were turned by 45° against the longest edge and by 90° against the previous layers. Figure 4c presents an example of the test samples made in the FFF technology and used in mechanical tests. In order to perform those tests, the Z030 universal testing machine, the HIT 50P pendulum impact tester, and the Z3106 hardness tester – all manufactured by Zwick/Roell (Germany) – were used.

RESULTS AND DISCUSSION

Grain size of ABS recyclate

It was found that the shredding of the plates in a cutter shredder provided recyclates with dominating grain sizes ranging from 2 mm to 7 mm, which constitutes 96.2%

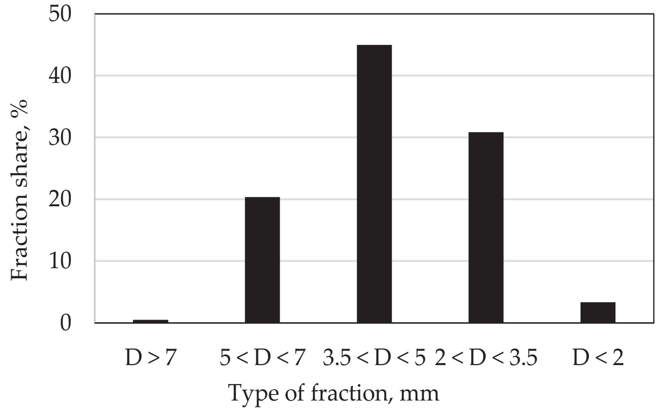

Fig. 5. The size particles distribution of the ABS copolymer recyclate

of the total sample mass (Fig. 5). Fractions with the grain size lower than 2 mm and higher than 7 mm constituted less than 4% of the entire recyclate. The obtained distribution of particle sizes is similar to a normal distribution, which is beneficial from the perspective of the secondary processing. The size of the dominating grains is similar to the size of granules of the original granulate. Such beneficial distribution of the recyclate grains arises from the appropriate parameters of the shredding process and the reproducible geometrical features of the initial feed (*i.e.* a housing with small dispersion of wall thickness).

Filament properties

In the process of extruding of ABS recyclates, the extrudate diameter varied within a range from 1.50 mm to 1.84 mm (extrudate average diameter $D = 1.66 \pm 0.05$ mm). Figure 6 demonstrates the distribution of this parameter. The analysis demonstrates that 94% of all the diameter measurement results fall within the range from 1.55 mm to 1.74 mm. This minor spread of values of the key filament dimension justifies its application in the FFF technology. It was found that the extrudate was characterized by the local thickenings of diameters in the range from 1.75 mm to 1.84 mm, which constitutes 3.6% of all the measurements. The reason for the local increase in the diameter is a spread observed in an apparent unstable viscosity, characteristic of a polymer alloy obtained from recyclates (segregation of an input material). Moreover, it was observed that the reason for the increase in a filament diameter was the infrequent occurrence of air bubbles throughout the whole volume of a filament which effected from not completely dried the input material.

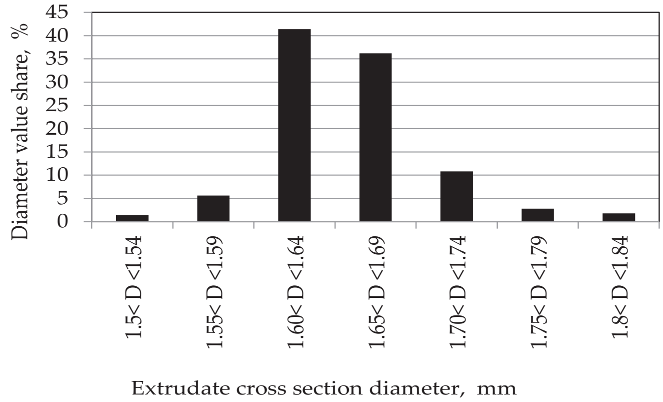

Fig. 6. Distribution of ABS filament cross-section diameter values

The following values of melt flow rate $MFR = 12.66 \pm 0.77$ g/10 min and of melt volume rate $MVR = 13.21 \pm 0.81$ cm^3/10 min observed for the ABS recyclate clearly show that the material can be used in both injection and extrusion. Observations of the material recorded during the plastometer test also allowed for the appropriate selection of processing settings (*i.e.* table temperature, head temperature, material extrusion rate, board and head movement velocity) to be applied during the process of additive manufacturing.

Mechanical properties

The comparison between sample runs of the tensile test of FFF specimens and injection molded pieces is demonstrated on Fig. 7. It can be observed that for both types of specimens, the curves are similar. Molded pieces are characteristic of higher values of tensile stresses but, when compared to the 3D printed elements, they are less flexible (see Fig. 7a). This results from the high pressure affecting the melted polymer on the phases of injection and holding. This gives rise to a solid material, where macro-particles are considerably closer to one another, which leads to higher van der Waals forces. Simultaneously, it can be observed that at the initial phase of the tensile test (until the deformation value of approx. 1.5%), the materials under research act in a similar manner. This stands for minimization of voids throughout the volumes of products, registered for the FFF technology [34]. Preliminary observations of fractures in the specimens made by the additive technique stand for the fact that a combination of both the applied adjacent threads and the product layers have been done well. The voids identified in the structure of the specimens during the static tensile test also seem to constitute an elastic phase and, therefore, the level of the true strain is higher than the one of injection molded pieces. The pieces obtained in the FFF technology are less susceptible to flexural tests (as can be seen on Fig. 7b), and the voids in the FFF specimens volume stiffen the material during the test. Yet another role of the voids can be observed in Charpy impact test (see Fig. 7c). The faster cracking of products manufactured additively confirms the fact that the crack propagation is more intense and it is the voids that are responsible for the areas of structural weakness of the material. The obtained effect increasing the elongation at break (approx. 20 per cent) in a static tensile test can be explained by the method of applying the outer contour of each layer. In the measured area, it

T a b l e 1. Test results of selected properties for samples made by injection molding technology and by FFF

Specimen	Tensile test			Flexural test			Impact test			
	Young's modulus MPa	Stress MPa	Strain %	Young's modulus MPa	Stress MPa	Strain %	Charpy kJ/m²	Impact tensile kJ/m²	Hardness MPa	Density g/cm³
IM	2309 ± 21	46.5 ± 0.9	2.93 ± 0.07	1838 ± 104	66.9 ± 0.3	5.21 ± 0.08	51.3 ± 9.8	162.8 ± 20	67.55 ± 2.5	1.038 ± 0.007
FFF	2155 ± 32	41.3 ± 1.3	2.82 ± 0.11	1771 ± 252	61.7 ± 1.4	6.12 ± 0.09	31.7 ± 3.9	115.4 ± 29	88.58 ± 7.5	1.041 ± 0.002

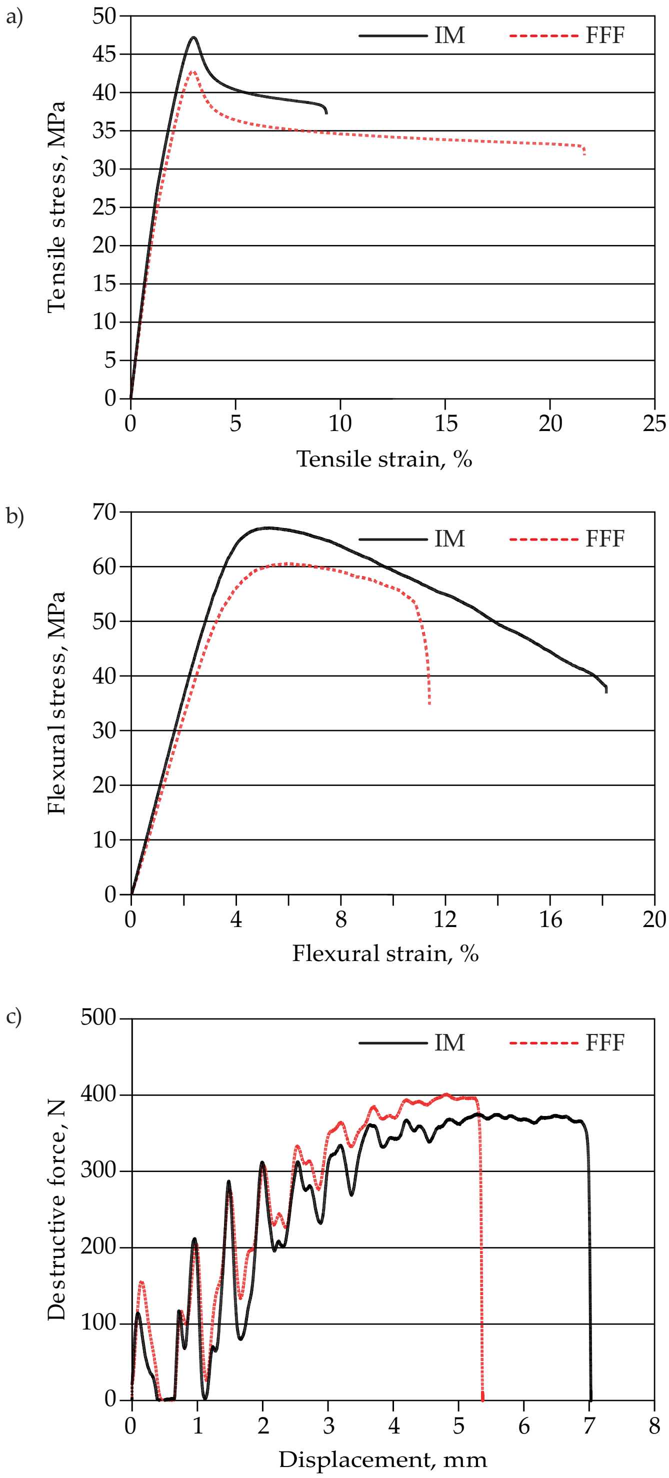

Fig. 7. Exemplary curves obtained during the tests of mechanical properties for specimens made by injection molding and by FFF: a) static tensile tests, b) three-point flexural test, c) Charpy impact tests

is compatible with the direction of the tensile force. At the same time, the maximum tensile stress (σ_m) with a similar elongation value for both types of samples can be observed. The identified voids in the FFF specimen structure cause by the accelerated cracking in the flexural and Charpy tests. In both these methods, the external load acts perpendicularly to the axes of the samples. For all used methods, a similar character of changes can be observed (Fig. 7). Despite the various technologies, the obtained average values of strength (σ) and modules (E) of samples differ by 8 to 10 per cent.

Table 1 presents results of the test of mechanical properties for the specimens manufactured by injection molding and by FFF.

To compare the results of the selected mechanical tests of samples made in the injection molding technology and those made in the FFF technology, a radar chart has been prepared (Fig. 8). The results for the injection molded samples are reference values (in black) for the samples made in the FFF technology (in red). The values of stress and Young's modulus (during the tensile strength test and the flexural test) for samples obtained in the FFF technology constitute 80 percent of the values of the mechanical properties of molded pieces made by injection. Deformation of the printed sample during

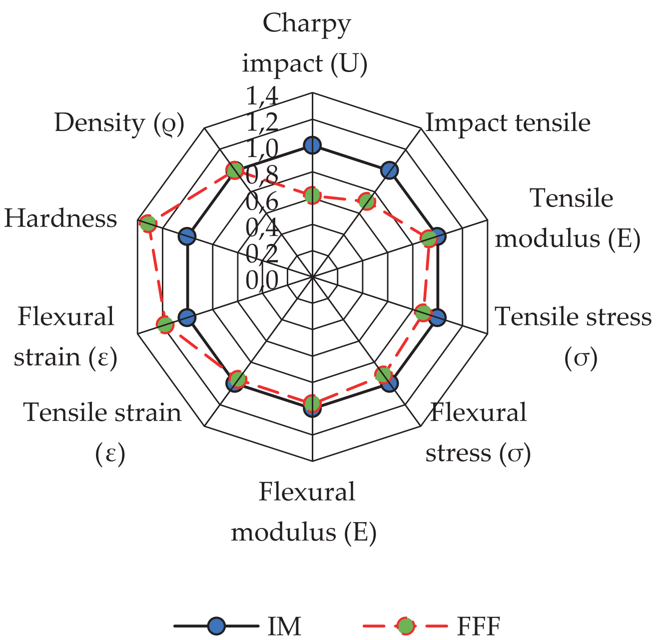

Fig. 8. Comparison of mechanical properties of samples made by injection molding (a black curve) and FFF (a red curve)

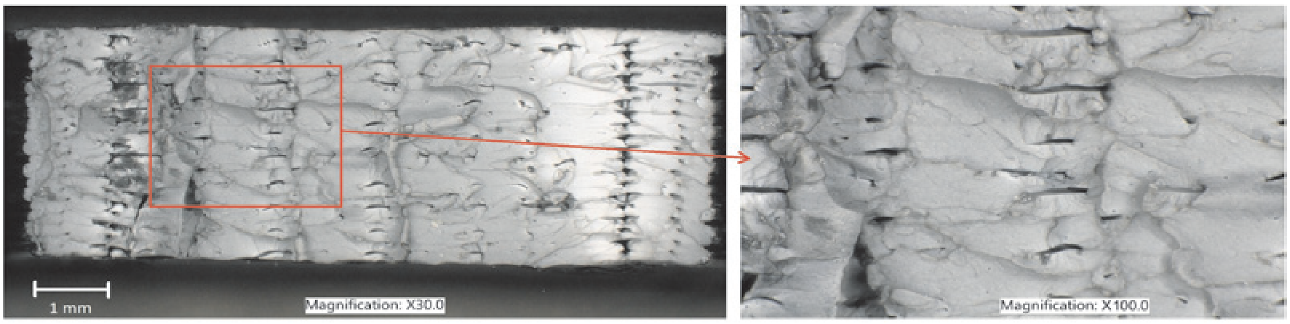

Fig. 9. Exemplary image of a fracture in the samples prepared by additive manufacturing (an enlarged view of layers and technological voids)

the tensile strength test is 96 per cent. Deformation during the flexural test, it equals 117.5 per cent of the values obtained for injection molded samples. Impact strength of the printed samples is considerably lower and ranges between 60 and 75 per cent in comparison with the solid ABS molded pieces. It was found that the hardness of FFF samples is higher by 31 per cent in comparison to the one of injection molded pieces. A high value of this material feature seem to have stemmed from the beneficial parameters adapted to layering the filament in the FFF technology. In this case, previous own experience has been used [34]. Despite the fact that the formerly mentioned technological voids in the structure of the ABS specimen have occurred, the registered images of the fractures confirm the fact that the consecutive threads and layers are packed and melted well (Fig. 9). This is evidenced by the favourable density results, which are higher by 0.8 per cent when compared to the one of molded pieces.

CONCLUSIONS

The conducted research confirm the possibility of secondary processing of used operating parts from 3D printers into a secondary filament which is meant to be applied in the FFF additive manufacturing technology.

The quality of manufactured components in the FFF technology is strictly related to the use of an insert material, characterized by reproducible processing properties and a possibly constant cross-section. The mechanical properties of the obtained products slightly differ from the ones of injection molded pieces.

In order to increase the mechanical properties of the products obtained by FFF, steps should be undertaken to increase the homogeneity and to minimize the technological voids in the structure of the obtained product. This can be achieved through modifying the processing parameters and changing the construction of the working head. This type of undertaking will increase the application possibilities of the manufactured products.

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