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Technical pathways for distributed recycling of polymer composites for distributed manufacturing: Windshield wiper blades

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ABSTRACT

Centralized waste plastic recycling is economically challenging, yet distributed recycling and additive manufacturing (DRAM) provides consumers with direct economic incentives to recycle. This study explores the technical pathways for DRAM of complex polymer composites using a case study of windshield wiper blades. These blades are a thermoplastic composite made up of a soft (flexible) and hard (less flexible) material. The distributed manufacturing methods included mechanical grinding to fused granular fabrication, heated syringe printing, 3-D printed molds coupled to injection molding and filament production in a recyclebot to fused filament fabrication. The particle size, angle of repose, thermal and rheological properties are characterized for the two sub-materials to define the conditions for the extrusion. A successful pathway for fabricating new products was found and the mechanical properties of the resultant components were quantified. Finally, the means to convert scrap windshield wiper blades into useful, high-value, bespoke biomedical products of fingertip grips for hand prosthetics was demonstrated. This study showed that the DRAM model of materials recycling can be used to improve the variety of solutions for a circular economy.

1. Introduction

Of the composite materials in production, polymer composites dominate in industry and thermoplastic composites have been growing rapidly in use (Yang et al., 2012). Unfortunately, the inherent heterogeneous nature of the composites leads to poor materials recyclability (Yang et al., 2012). As overall polymer recycling is only 9% globally, with the overwhelming majority of global plastic waste being land filled or ending up contaminating the environment in some way (Geyer et al., 2017), it can be safely assumed that polymer composite recycling is nearly non-existent. This is in part due to the technical complexity, but also because these composites are not labeled for recycling in major economies like the U.S. and current law does not enable consumers to be informed about the materials making up their products (Pearce, 2018). Although some countries, like China, have a far more robust recycling code system (SAC, 2008), even if a polymer composite is technically recyclable, it is not marked for recycling from post-consumer waste. This issue is compounded by the recent Chinese import ban on waste plastic (Brooks et al., 2018), which effectively blocks polymer recycling from the largest global recyclers.

One technical area that provides some hope for expanding plastic waste recycling is the new circular economy concept of distributed recycling for additive manufacturing (DRAM) (Zhong and Pearce, 2018). The open source 3-D printing community (De Jong and de Bruijn, 2013) has already started to adopt a complex voluntary recycling code system that can be adapted for polymer composites (Hunt et al., 2015). As distributed manufacturing is still in its infancy, this method does not have a large impact on global plastics end use, however, as the global value chains continue to shift (Laplume et al., 2016), this pathway could become important. This is possible because of the superior economics of distributed manufacturing, where direct production by prosumers offers significant cost savings compared to

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purchasing mass-manufactured products (Gwamuri et al., 2014; Wittbrodt et al., 2015). Substantial savings are observed for scientists and engineers manufacturing scientific tools (Pearce, 2012, 2014; Baden et al., 2015; Coakley and Hurt, 2016; Beeker et al., 2018; Hietanen et al., 2018), technically-sophisticated prosumers making consumer products (Wittbrodt et al., 2013) as well as average consumers making everyday items (Petersen and Pearce, 2017). Distributed manufacturing savings on the order of 90% or more are found for products ranging from medical supplies and adaptive aids (Gallop et al., 2018) to children's toys (Petersen et al., 2017).

Economic incentives for consumers can be expanded further with the concept of distributed recycling coupled to distributed AM (Zhong and Pearce, 2018). This was first done by upcycling plastic waste into 3-D printing filament with an open source waste plastic extruder known as a recyclebot (Baechler et al., 2013). Using a recyclebot decreases the embodied energy of 3-D printing filament by 90% (Kreiger et al., 2013, 2014; Zhong et al., 2017). Following the self-replicating rapid prototyper (RepRap) model (Sells et al., 2007; Jones et al., 2011; Bowyer, 2014) a recyclebot has been designed that is largely itself 3-D printed (Woern et al., 2018). Many recyclebot versions have been developed (Appropedia, 2019). As the use of a recyclebot system introduces a melt and extrude cycle, which is known to impair the mechanical properties (Hyung Lee, et al., 2012; Oblak et al., 2015) and limits the recycles to about five (Cruz Sanchez, et al., 2017; Santander et al., 2018) without using some means of reinforcement or blending with virgin materials. In addition, fused particle fabrication (FPF) or fused granular fabrication (FGF) 3-D printers can fabricate products directly from shredded plastic waste or pellets (Volpato et al., 2015; Beaudoin, 2016; Giberti et al., 2017; Liu et al., 2017; Whyman et al., 2018) and have been used for recycled materials (Woern et al., 2018b; Byard et al., 2019; Reich et al., 2019). Other recent studies have looked at using 3-D printing for recycling of advanced applications like batteries (Singh et al., 2019a) and for multi-materials (2019b).

Many research groups and companies have demonstrated that pre-consumer and post-consumer waste polymers can be recycled into 3-D printing filaments or directly printed, including: polylactic acid (PLA) (Cruz Sanchez, et al., 2015, 2017; Anderson, 2017; Pakkanen et al., 2017; Woern et al., 2018), acrylonitrile butadiene styrene (ABS) (Mohammed et al., 2017a,b; Zhong et al., 2018), high-density polyethylene (HDPE) (Baechler et al., 2013; Chong et al., 2017; Pepi et al., 2018), polypropylene (PP) and polystyrene (PS) (Pepi et al., 2018), thermoplastic polyurethane (TPU) (Woern and Pearce, 2017); polyethylene terephthalate (PET) (Zander, et al., 2019; Zander et al., 2018), linear low density polyethylene (LLDPE) and low density polyethylene (LDPE) (Hart et al., 2018), polycarbonate (PC) (Reich et al., 2019). These studies focused on single types of polymers. Only a few studies have looked at making filament from polymer composites using carbon reinforced plastic (Tian et al., 2017), fiber filled composites (Parandoush and Lin, 2017; Heller et al., 2019) and various types of waste wood (Pringle et al., 2018; Zander, 2019).

This study explores the technical pathways for distributed recycling of polymer composites for distributed manufacturing, which is summarized in Fig. 1. To illustrate the options for these pathways a case study is performed on windshield wiper blades, which are a thermoplastic composite made up of a soft (more flexible) and hard material to meet the exacting needs of the automobile industry. First, the percentages of each sub-material are quantified and particle size analysis is performed on the mechanically sized-reduced composite waste. The angle of repose is calculated for the material. Then the thermal and rheological properties are characterized for the two sub-materials to help define the conditions for the extrusion. In addition, the viscosity with the storage (elastic - G') and loss (viscous - G") modulus is characterized. The sub-materials are analyzed using the following techniques: differential scanning calorimetry (DSC), Fourier-transform infrared spectroscopy (FTIR), thermomechanical analysis (TMA), thermal gravimetric analysis (TGA), and rheological analysis. Then, the composite material waste is tested in each of the pathways shown in Fig. 1. These include first mechanical grinding, then the particles are (1) converted to filament using a recyclebot and 3-D printed using fused filament fabrication (FFF), (2) the particles are directly printed with FPF, (3) the particles are directly printed using a syringe printer and (4) the particles are injection molded in a custom 3-D printed mold. The results are discussed and conclusions are drawn in the context of distributed recycling and manufacturing using AM for complex composite polymer materials.

2. Material and methods

2.1. Materials

Fig. 2 shows the starting material of a windshield wiper blade with the two materials labeled. It was industrial waste from a automobile component manufacturer. Material 1, which is against the windshield glass in operation, is more flexible and then the rigid material 2 is used to connect to the wind shield wiper frame. Mechanically ground windshield wiper blade (both materials combined) was provided by McDunnough Plastics, Fenton MI for \$1/lb (\$2.20/kg). The ground combination of material had a range of particle sizes.

The particle size characteristics and distribution of the starting material was quantified using digital imaging with the open source Fiji/ImageJ Likewise, to understand the ability of the particles to flow, imageJ was used to find the angle of repose (a_r) of the material. When determining the a_r, the selected particle must be piled as high as it can go within a certain base diameter (Al-Hashemi and Al-Amoudi, 2018). Basic piling (funnel method) and the alternative method using the dish technique with a set radius (Kurkuri et al., 2012) was repeated three times for each method. The diameter (d) is measured as well as the height (h) of the particles and the angle of repose (a_r) was determined by:

$$a_r = \arctan\left(\frac{h}{d}\right) \tag{1}$$

Some of the material was mechanically separated by hand and massed on a digital scale (+/−0.01%) to determine the percent of each material. Three separate trials were completed to give average of the total mass of the sample, the hard material and the soft material.

2.2. Material characterization

For the materials characterization tests (DSC, FTIR, TGA, and TMA), the material starting commingled material (material 1 and material 2) was separated into the hard and soft components. The characterization tests were performed using an amount that was enough to be representative of the sub-material behavior for each test.

2.2.1. DSC

The DSC tests are performed using the DSC822e Mettler Toledo and the results were analyzed using the STARe software. The tests were performed in a controlled environment under nitrogen and within a temperature range from 25 °C to 200 °C. The three different heating and cooling rates were 2 °C/min, 10 °C/min and 40 °C/min.

2.2.2. FTIR

FTIR analysis were performed using the Thermo Scientific Nicolet iS5 FTIR spectrometer combined with OMIC Semec software to obtain an infrared spectrum of absorption or emission of a solid, liquid or gas. The wave number scan was set from 4000 cm^{-1} to 525 cm^{-1} with 4 cm^{-1} resolution.

2.2.3. TGA

TGA is an experimental technique to measure mass as a function of

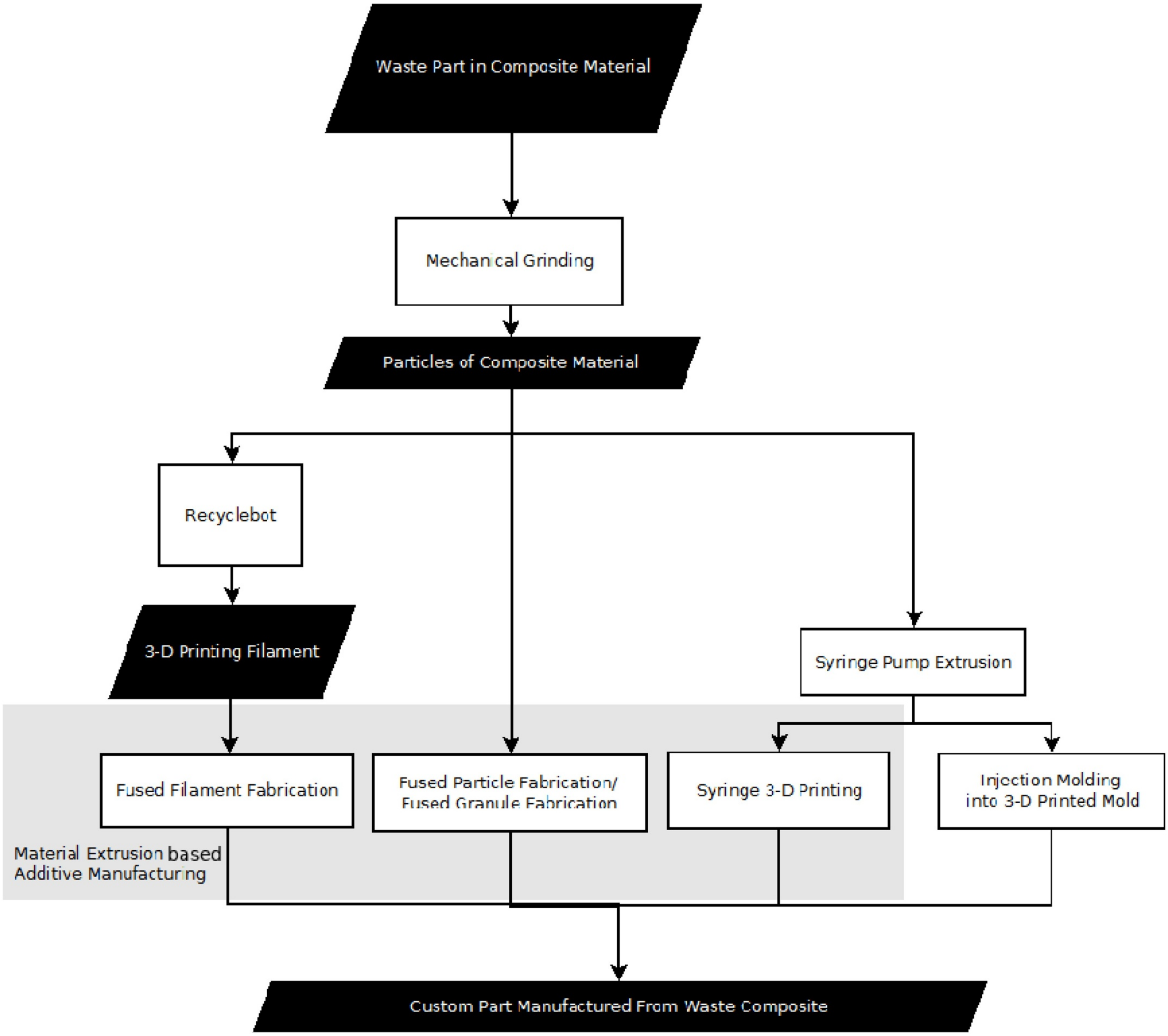

Fig. 1. Technical pathways for distributed recycling of polymer composites for distributed manufacturing.

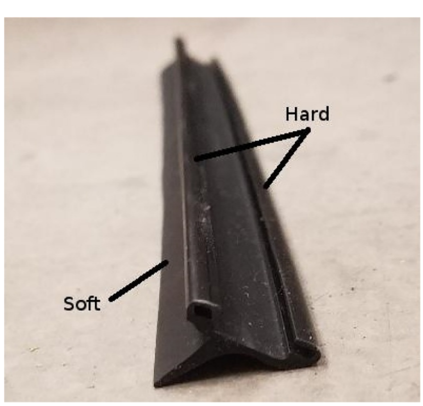

Fig. 2. Image of windshield wiper.

temperature; hence, it can accurately determine moisture loss, loss of solvent or plasticizer and decomposition of the material (Basu, 2013) and indicate the amount of any inorganic material in a sample. The FTIR spectroscopy results of the sub-materials investigated in this work showed that one of the difference was an extra C—N or C—C bond for the soft material. In order to identify which of the two polymers had the additive, TGA analysis was performed at a heating rate (20 °C/min) chosen from the literature (Gu and Liang, 2003). TGA/DSC 1 - Mettler-Toledo with STARe software system was used.

2.2.4. TMA

TMA tests were performed on TMA/SDTA840 Mettler Toledo and the results are analyzed on STARe software. The tests were performed in a controlled environment using nitrogen and within a temperature range from 25 °C to 250 °C.

2.2.5. Rheological tests

The equipment used for the rheological tests was the Kinexus pro+ with a cone probe. It is a rotational rheometer and it has the ability to measure the viscosity, loss and storage modulus (G' and G"). The shear rate for the extrusion process should be between 1 and 100 s^{-1} in this testing system and for completeness the tests were run from 0.1 to

100 s^{-1} at 180 °C. The polymer was provided in small pieces, and in order to perform the rheological tests it was ground into a fine powder.

2.3. Processing

3-D printing filament made from the composite material was fabricated with a vertically-mounted recyclebot previously described (Zhong and Pearce, 2018). Material was extruded at 240–270 °C and a speed of approximately 10 rpm. The material was placed in funnel-like hopper that was fed into a hot zone with an auger. Filament was extruded and the diameter held constant with a position sensitive photodetector that maintains a constant tension on the material as it is spooled.

The filament created by using the vertical recyclebot was inserted into an adapted delta-style RepRap 3-D printer (Anzalone et al., 2015) that can print flexible materials (Olson, 2018). The designs were sliced with Cura 21.03 slicer and Franklin firmware (Wijnen et al., 2016). The initial extrusion temperature was set to 260 °C and was slowly increased to 290 °C. The slice and majority of other settings were left at the default values. The bed was not heated, but glue was applied for bed adhesion.

Similarly, the same filament was used in an open source Lulzbot TAZ 6 FFF 3-D printer (Aleph Objects, Loveland, CO) to print the material from Cura 21.03 slicer and Marlin firmware. The extrusion temperature was set at 260–290 °C with a build plate temperature of 60°C.

A prototype open source Gigabot X (re:3D, Austin, TX) FPF/FGF 3-D printer was used to print the ground materials directly. 3-D models were sliced with Slic3r and the printer was controlled with Marlin Firmware. The extrusion temperature was set at 260–290°C with a build plate temperature of 60 °C.

Similarly, a delta-style RepRap 3-D printer was used in stage mode (Zhang et al., 2016) with an open-source syringe pump (Wijnen et al., 2014) to print the particles directly. The bed was not heated, but the extrusion temperature was set at 270°C.

Muhammad et al., used a 3-D printed molds from ABS after failed attempts at printing large water fixtures with recycled HDPE waste in the Solomon Islands (Mohammed et al., 2019a; Mohammed et al., 2019b). This method has been adapted to take advantage of the higher melting point of PC (Reich et al., 2019) so low-cost molds were designed for use in an injection molder. The molding machine consists of a metal tube surrounded with heating elements and a manual plunger to push material through the hot zone into the mold. The tube is filled with plastic and the mold is then screwed onto the heated tube with a flange, and the plunger pushes the molten plastic into the mold cavity. The system was operated at 280 °C.

2.4. Mechanical properties of manufactured parts

Five tensile specimens of the material were manufactured using injection molding into 3-D printed polycarbonate molds following a procedure previously discussed (Reich et al., 2019) using an injection temperature of 280 °C and preparation time of approximately five minutes. The specimens were according to ASTM D638 type IV standards adapted for 3-D printing materials (Laureto and Pearce, 2018). The specimens were then pulled until failure using a 10,000 lb. load cell (Model LCF455). The strain data was captured using the cross-head extension on the Universal Testing Machine.

2.5. Application demonstration

One of the most media-covered applications of consumer-grade 3-D printing is Enabling the Future (enablingthefuture.org) or e-NABLE, which is an online global community (Fig. 3) of ~20,000 "digital humanitarian" volunteers who use their 3-D printers to make free and low-cost open source prosthetic upper limb devices for children and adults in need (Schull, 2015;Silva et al., 2015; Wu et al., 2016; Gwamuri et al., 2016; Novak, 2019).

The standard e-NABLE hands are printed in hard thermoplastics and a relatively expensive kit comes with rubber like fingertips to aid gripping. As a demonstration of DRAM, the recycled windshield wipers were used to offset the costs of these tips for an e-NABLE Phoenix style hand. 3-D printed finger-tip molds were created by taking the original finger design from the prosthetic hand and cutting off the bottom half in Blender. The mold geometry was made by using the Lulzbot Cura slicer function "mold" under special modes. These altered fingers (Fig. 4a) and tips (Fig. 4b) were subsequently printed with PLA and the molds printed polycarbonate, respectively. An self built injection molding machine consisted of a tube heated with a nichrome wire coil and a manually-operated plunger is used to inject the melted mixture into the mold. In order to use theinjection molding machine (discussed in detail in Meyer et al., 2020) the mold was secured between the metal nozzle and a flat metal piece using four socket head M4 × 40 screws and four M4 nuts. The mold was moved to each finger by using a pair of pliers in order to properly obtain five finger-tips. These were then epoxied onto the other half of the finger (Fig. 4a).

3. Results

After the separation and mass tests the composite material was found to be 29.5% hard material and 70.5% soft material by mass. Fig. 5 shows the distribution of particle size of the windshield wiper components with a separation between particles smaller than an area of 1.153 mm^2 and larger than 1.153 mm^2 of a particular sample.

Three trials were performed to find the angle of repose using the funnel method shown in Fig. 6a and for the petri dish method shown in Fig. 6b. Using the funnel method, the average calculated angle of repose was determined to be 56.2° with a standard deviation of ± 4.3 and with the petri dish method, the average calculated angle of repose was determined to be 55.6° with a standard deviation of ± 3.2. The results shown in Fig. 6 indicate that the high density of the soft material and the uneven geometries led to a high angle of repose, which can cause flow challenges for feeding the material in the various DRAM methods (e.g. high angle of repose prevents particles from flowing through the hopper to the working end causing non-uniformity in output).

Fig. 7 shows the DSC thermal test results at 2 °C/min scans as well as the other tests for the hard polymer.

The values of the melting and crystallization temperature at different rates are reported in Tables 1 and 2.

The results show similar trends and similar values.,There is roughly a greater than 10 °C difference in melting temperature between the two materials. For the sub-material classified as "hard polymer", the glass transition temperature (T_g) is strongly affected by the heating rate; hence it is difficult to identify the exact value.

For the sub-material classified as "soft polymer", there is no significant variation of the melting temperature value with the heating rate. On the other hand, for the hard polymer the melting temperature for 2 °C/min and 10 °C/min rate does not change much and it increases drastically at 40 °C/min heating rate. For both sub-materials, the crystallization temperature (T_c) is higher at 2 °C/min compared to the one for 10 °C/min. This might be due to more double bonds in the hard polymer and this will be discussed in more detail in the FTIR section. These results, however, show that finding an ideal temperature to 3-D print the materials is challenging, as it is not only a temperature, but also the rate the heat is provided is important.

The two polymers show similar infrared spectra with the only difference being the peak at 1593.3 cm^{-1} observed in the hard polymer (Fig. 8 left). This particular peak represents either a C—N or C—C single bond, which is responsible for the greater hardness. The spectrum of the soft material shows a peak just above 1593.93 cm^{-1} which corresponds to a C═O double bond. The peak at 3358.39 cm^{-1} could represent either an O—H or an N—H single bond. In some cases this peak is also related the moisture content. The larger peaks in both spectra are 2918,

Fig. 3. Map of e-NABLE volunteer chapters throughout the world.

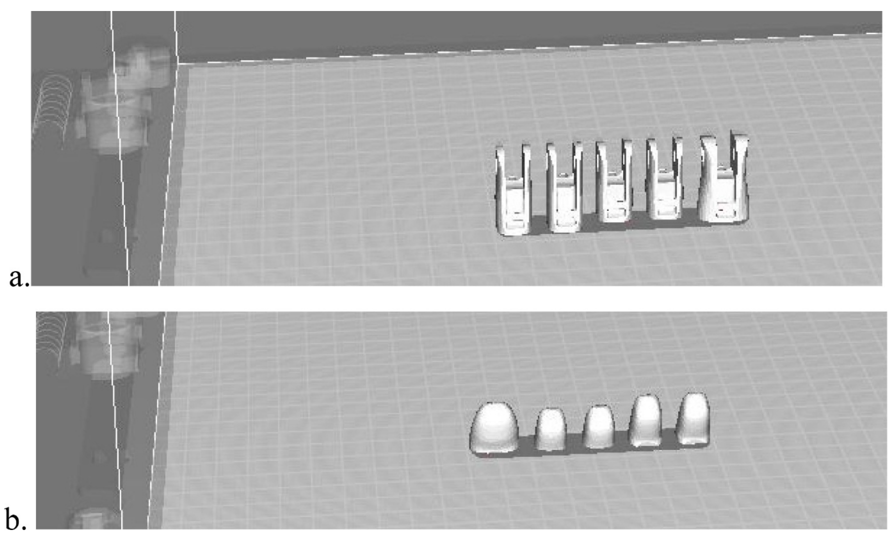

Fig. 4. The (a) adapted fingers without tips and (b) the tips used to slice into molds.

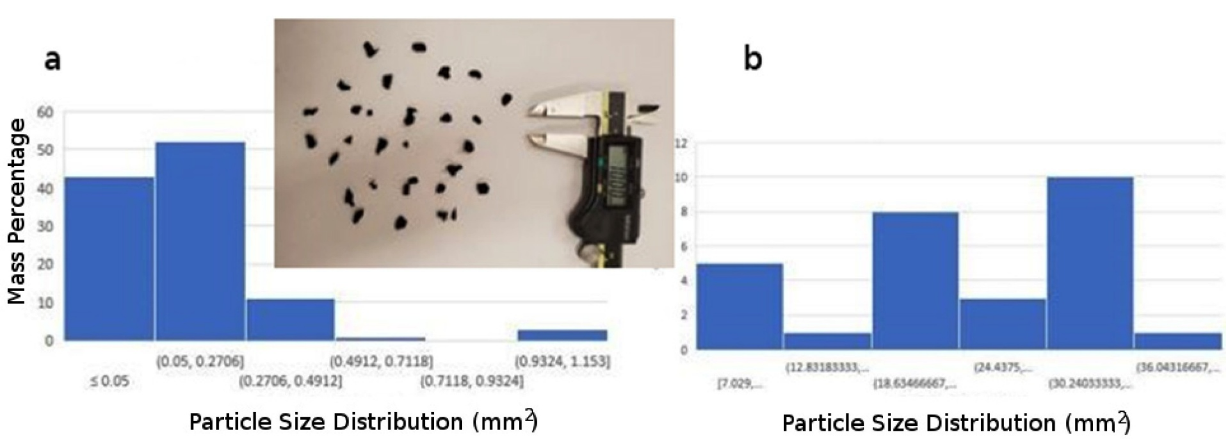

Fig. 5. Particle size analysis distribution (a) for particles <1.15 mm^2 and (b) for particles >1.15 mm^2 along with inset of example analysis image.

Fig. 6. Angle of repose analysis (a) funnel method and (b) petri dish method.

2850, 1455, 1375, 1015, 720 and 668 cm^{-1} which are all indicating C–H stretching or bending vibrations.

Fig. 9 shows the results of the TGA tests for the two sub-materials. The hard polymer decomposes in a single stage and loses almost 95% of the material. The decomposition starts at 312 °C and the polymer is stable up to this temperature. At the end of the test at 500 °C, there is only 2% carbon material left.

The soft polymer decomposes in two stages. The first stage is from

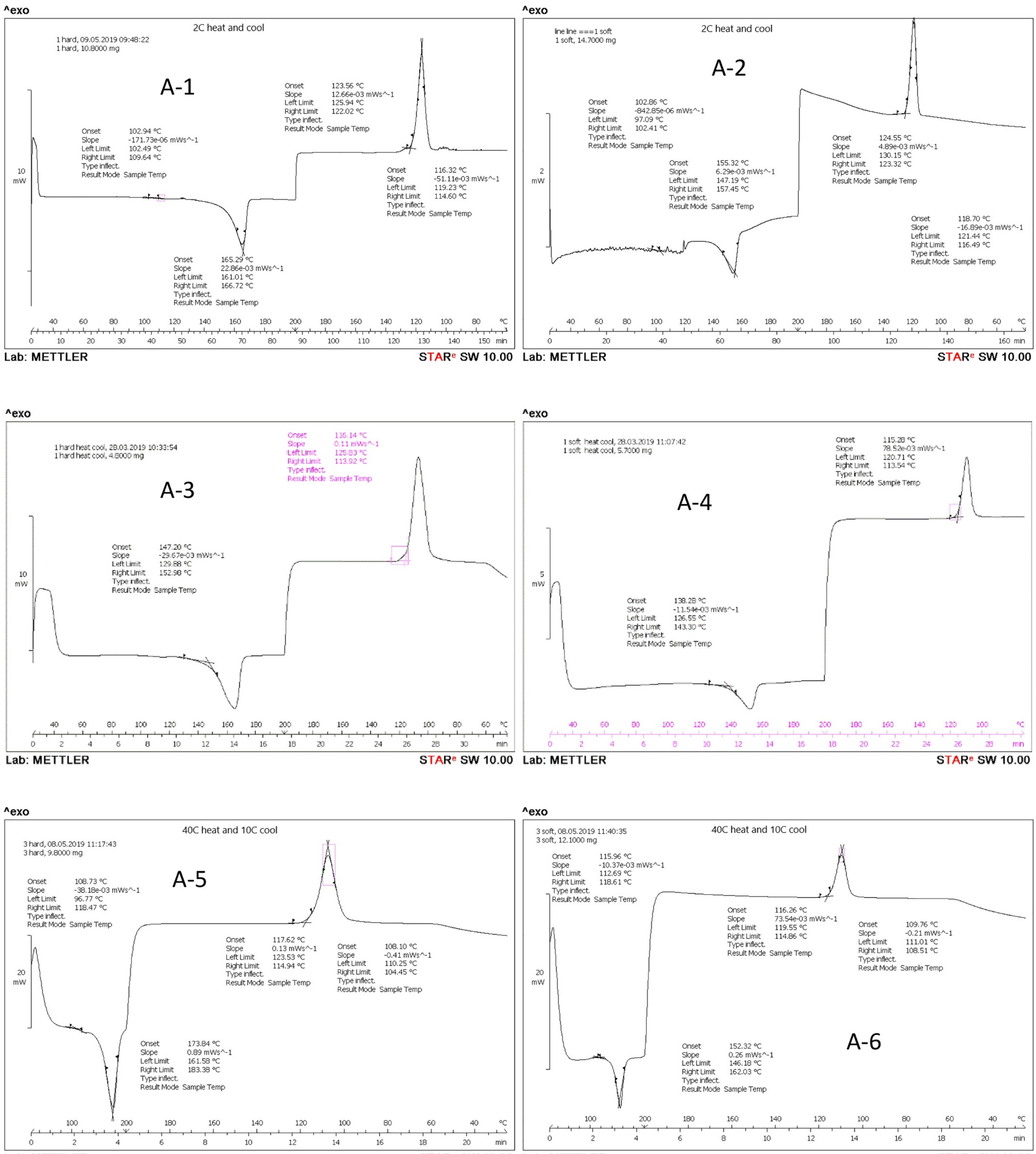

Fig. 7. A-1: Hard polymer at 2 °C/min heat and cool, A-2: Soft polymer at 2 °C/min heat and cool. B-1: Hard polymer at 10 °C/min heat and cool, B-2: Soft polymer at 10 °C/min heat and cool. C-1: Hard polymer at 40 °C/min heat and 10 °C/min cool, C-2: Soft polymer at 40 °C/min heat and cool.

Table 1
Melting and crystallization temperatures of hard polymer.

	Melting temperature (tm)	Crystallization temperature (tc)
2 °C/min heat and cool	165.29	123.56
10 °C/min heat and cool	165.55	115.75
40 °C/min heat and 10 °C cool	177.32	115.41

Table 2
Melting and crystallization temperatures of soft polymer.

	Melting temperature (Tm)	Crystallization temperature (Tc)
2 °C/min heat and cool	154.90	125.46
10 °C/min heat and cool	153.10	115.6
40 °C/min heat and 10 °C cool	154.20	115.34

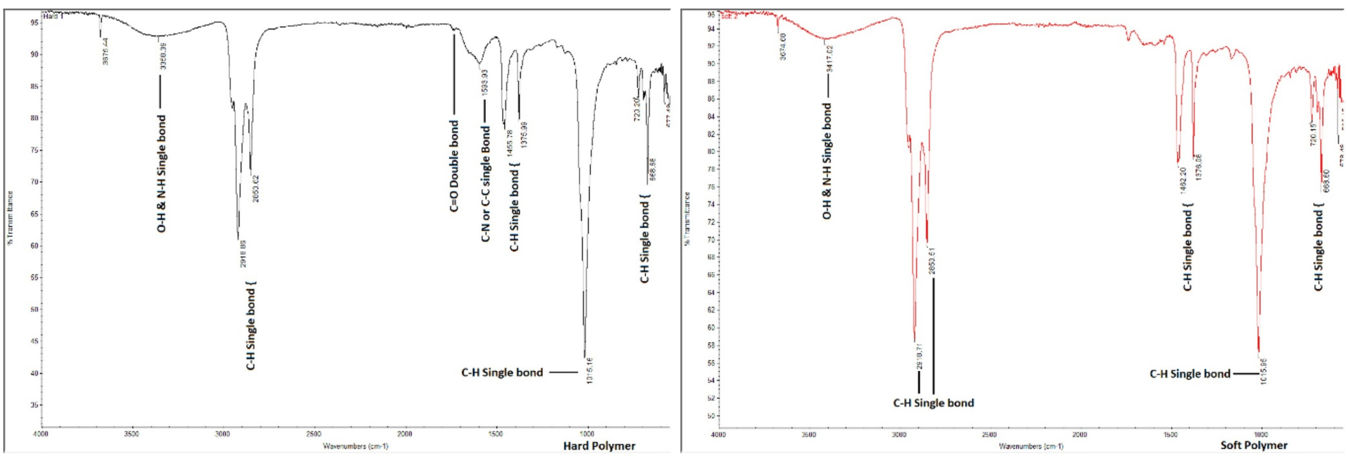

Fig. 8. Infrared spectrum of hard polymer (left) and soft polymer (right).

250 °C to 420 °C, during which it loses approximately 25%, and the second stage is from 420 °C to 500 °C during which there is a further 54% loss. The first loss is caused by the softening of the polymer and the latter is responsible for the rapid decomposition in the second stage. The lower temperature at which the decomposition starts for the soft polymer might be due to a lower molecular weight or shorter chains. The 20% remaining inorganic material indicates that an additive such as a plasticizer, used to change the properties of the rubber, was added to the soft polymer. This again adds to the complexity of finding a processing window for conventional material extrusion for the two polymers when they are mixed, as is the case for the waste from windshield wipers.

Fig. 10 shows the results of the TMA tests for the hard polymer.

For the hard polymer, the following temperature values were measured: Glass transition temperature $T_g = 155$ °C–160 °C; crystallization temperature $T_c = 162$ °C; and melting temperature $T_m \sim 168$ °C. It was also observed that as the temperature increased, the hard polymer initially expanded by approximately 11% until it reached the T_g value. Further temperature increase after the melting point at 168 °C caused the length of the sample to decrease, reaching 0.01% of the original size at 250 °C. Quantitative comparisons of the values observed for the hard and soft polymer are shown in Table 3.

In order to minimize the effects of the above-mentioned shrinkage, the extrusion temperature should be as close as possible to the melting temperature. However, from the DSC results it was observed that the melting temperature at a heating rate of 40 °C/min can increase up to 177 °C (Fig. 7). This requires the extrusion temperature to be at least 180 °C in order to achieve complete melting of the extruded material. However, in practice this temperature needed to be much higher because of the low thermal conductivity of the materials.

Fig. 11 shows TMA test results for the soft polymer.

For the soft polymer, the following temperature values were measured: Glass transition temperature $T_g \sim 130$ °C; crystallization temperature $T_c \sim 140$ °C; and melting temperature $T_m \sim 150$ °C. The soft polymer shows a small volume reduction around T_g and above the T_m it starts to expand at a constant rate by approximately 11% of the initial volume at 240 °C. The extrusion temperature for the soft polymer is 150 °C. However, due to the small percentage increase in volume, it can be extruded at 180 °C since at this temperature the polymer expands slightly by approximately 3–5%. This would allow overcoming the problem of separately extruding them.

Fig. 12 shows the viscosity as function of the shear rate for the hard and soft polymer.

The viscosity of the hard polymer ranges from 4220 Pa s to 2930 Pa s for 0.1 s^{-1} shear rate. The soft polymer has a viscosity ranging from 36,200 Pa s to 26,300 Pa s at the same shear rate value as the hard polymer. The lower viscosity for the hard polymer represents a more favorable property for the extrusion process since the viscosity is approximately ten times lower than that of the soft polymer. However, both polymers could be suitable for 3-D printing if a sufficiently high extrusion speed is used (Osswald and Rudolph, 2014).

In the most common path for 3-D printing (FFF) shown in Fig. 1, the vertical recyclebot was able to successfully make filament as seen in Fig. 13. This indicates the material could also be intrusion molded, which is the combination of extrusion and injection molding. This process is left for future work.

Although fabricating filament was possible and the first small test print on the delta RepRap 3-D printer worked successfully with this material, afterwards the print would continue to fail due to nozzle clogging. The same behavior was observed on the Lulzbot Taz print

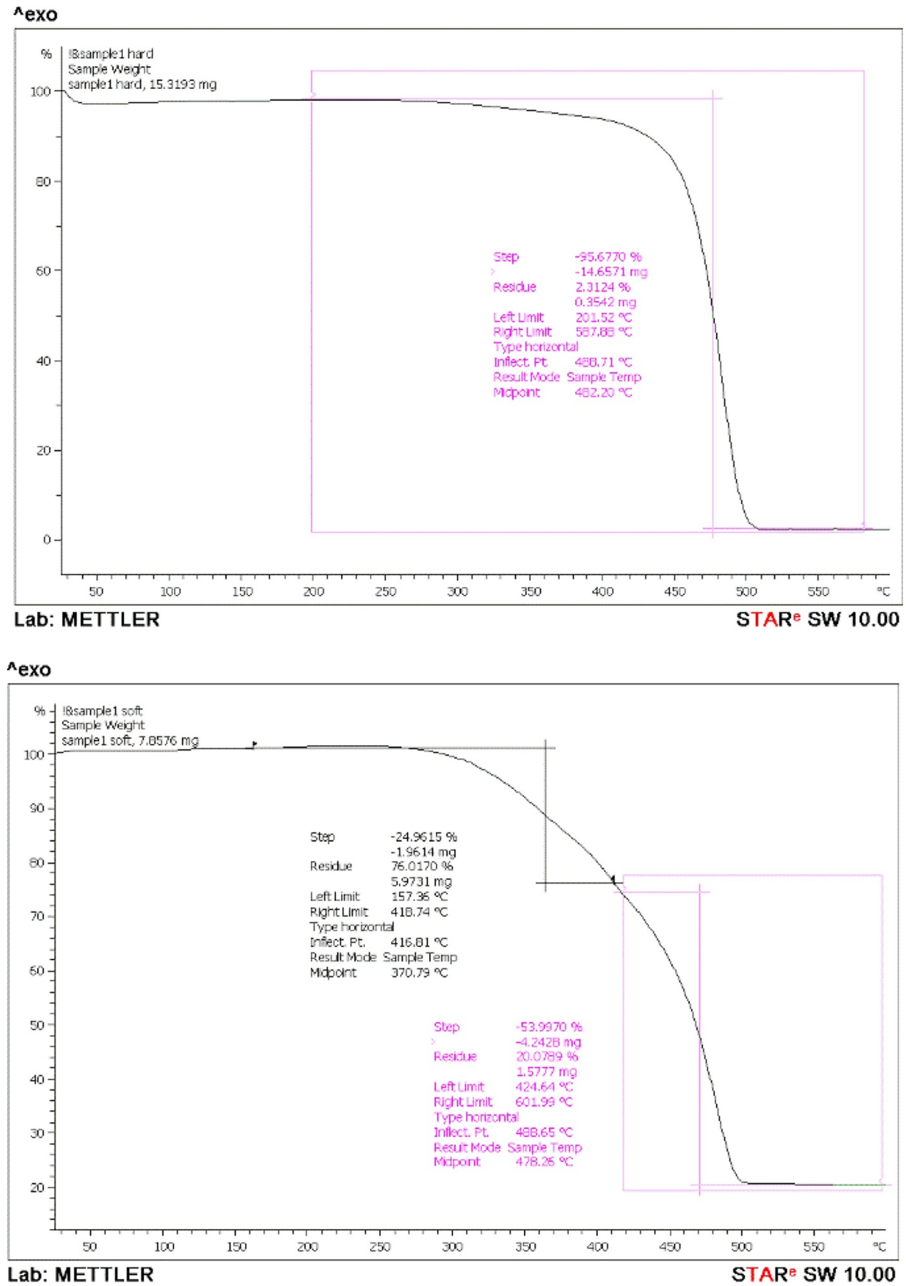

Fig. 9. TGA analysis of hard polymer (left) and soft polymer (right).

tests. Similarly, the FPF printing and the direct syringe pump also proved unsuccessful. The former due to challenges in feeding and clogging and the latter because of the inability to obtain extrusion in the setup (higher temperatures and more rigid framing may make such printing possible, however challenges remain in obtaining uniform heating over a large volume to make printing practical). Finally, after many failed tests the material was found to be injection moldable in a 3-D printed polycarbonate (PC) mold, which is shown in Fig. 14.

As can be seen in Fig. 15, although there was some variation in the mechanical properties that can be ascribed to the increased mass, the wind shield wiper material had an average peak stress of 7.34 MPa with a standard deviation of 2.785. The average strain during breaking was 122.13%.

The material can be compared to a commercial flexible 3-D printing material. Fig. 16 shows this comparison between Ninjaflex filaments that was 3D printed according to ASTM D638 type I standard and the windshield material that was molded according to type IV standard. The stress values at 100% strain for the windshield specimens are close to the stress values for Ninjaflex filament at 100% strain (Tanikella et al., 2017). However, while Ninjaflex filament continues to expand to over 500% strain without failure, the windshield material fails at an average strain of 122%. Hence, the windshield material is more brittle than Ninjaflex, but for strain rates less than 100%, they have a similar behavior under tensile load. From the results it is clear that the recycled windshield specimens are not consistent, due primarily to the variations in the mass, caused by voids within the specimens, due to which failure is not consistent and there is a high standard deviation in the peak stress. However, for many applications the quality of the recycled material may still be more than what is required. Future work is needed to do a detailed comparison with Ninjaflex. In addition, past work on the geometric properties (Lanzotti et al., 2015; Garcia-Plaza et al. 2019) and process parameters (de Ciurana, et al., 2013; Chacón et al., 2017) on the impact of FFF component mechanical properties (Tymrak et al., 2014) can be repeated for these recycled

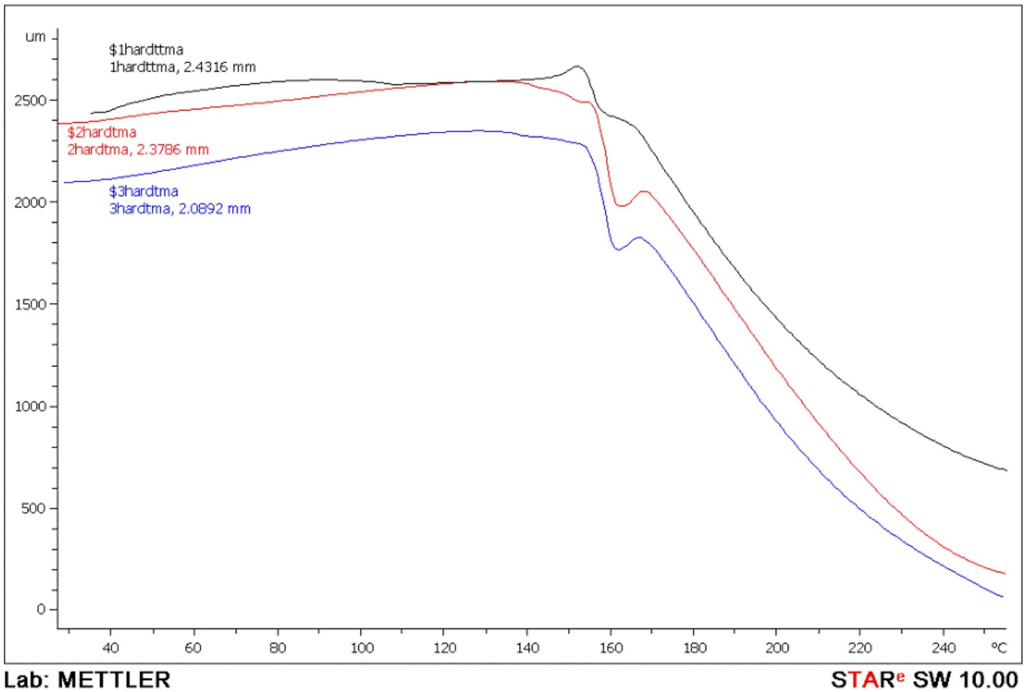

Fig. 10. TMA analysis results of hard polymer.

Table 3
Comparison of the percentage shrinkage at two temperatures of hard polymer.

Hard polymer	Percentage shrinkage 170 °C	180 °C
Sample 1	7.4%	19.2%
Sample 2	13%	30.1%
Sample 3	13.5%	28.4%

materials. In addition, if the properties are not adequate for a given application creating a composite with a reinforcing agent can be investigated (Caminero et al., 2019).

This recycled material is normally sold to compounders who use it as part of a formulation to make specific product (compounded resin). This product will usually be molded into something that is slightly flexible with good weatherability. Here a high value uses of the material were demonstrated using 3-D printing custom molds to make prosthetic hand with recycled windshield wiper finger tip grips (Fig. 17).

4. Discussion

The global additive manufacturing market is expected to grow to US $ 36.61 billion/year by 2027 from US$ 8.44 billion/year in 2018

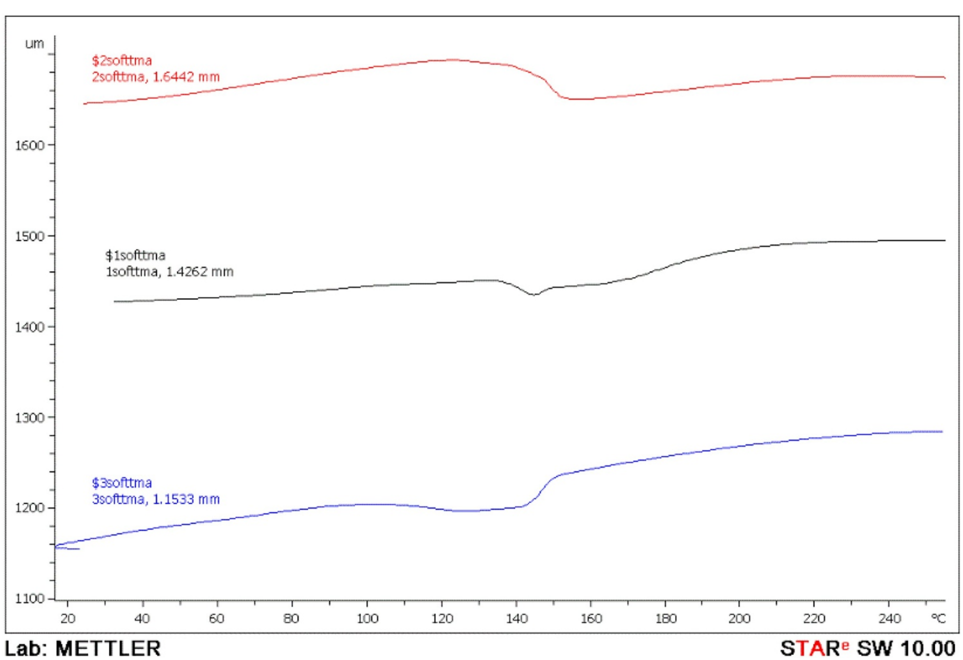

Fig. 11. TMA analysis results of soft polymer.

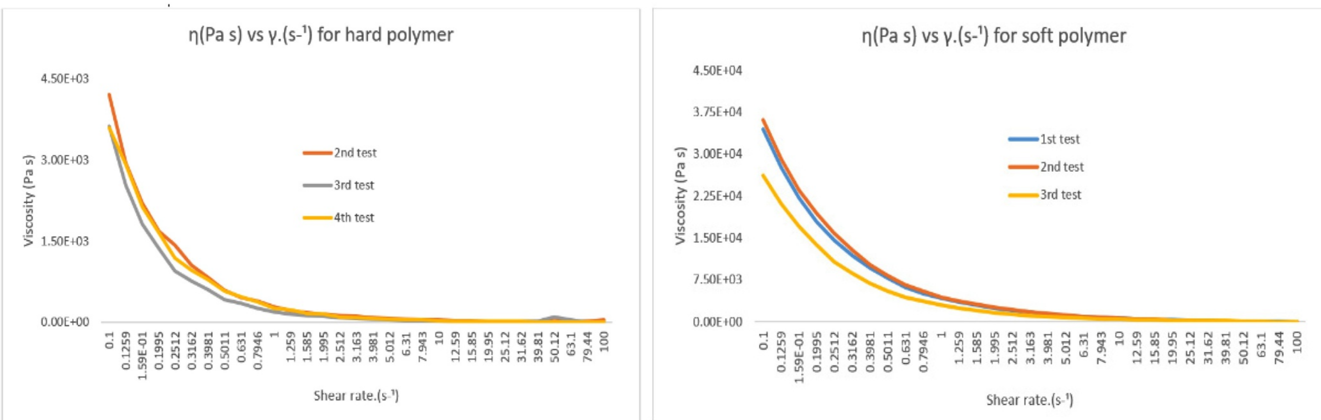

Fig. 12. Viscosity for hard (left) and soft polymer (right) vs shear rate.

Fig. 13. 3-D printing filament made from waste composite.

Fig. 14. The polycarbonate printed finger tip molds after use.

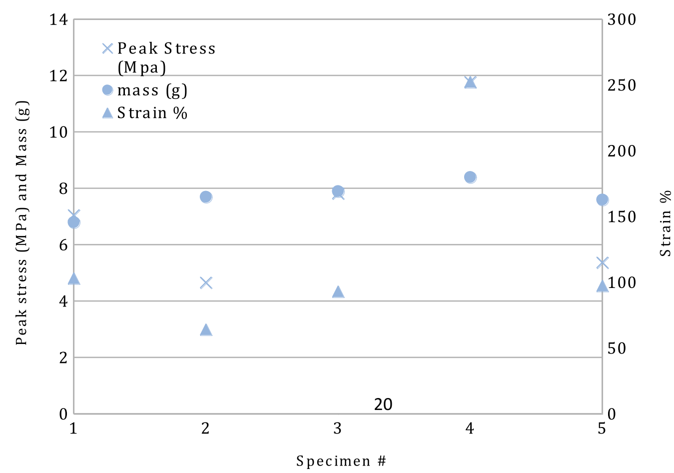

Fig. 15. Peak stress (MPa) and mass (g) on left axis and percent strain on right axis of tensile bar tests made with the wind shield wiper material.

(RB, 2019). Other estimates expect the AM market to reach over US$ 41 billion from a current value of US$9.3 billion (3D Natives, 2018). Of the total market, the vast majority of 3-D printing is still thermoplastic-based, and in 2018 polymeric additive manufacturing has reached nearly US$5.5 billion (3D Natives, 2018). If the materials fraction of the market grows as expected, it will reach about US$10 billion. Overall, the global commodity plastics market is US $342.65 billion in 2017 and is expected to reach US$686.56 billion by 2026 (CPM, 2018). This would mean that by 2026 AM plastic would result in about 1.5% of the overall plastics market. However, there are several reasons to believe that this may grossly underestimate the potential for distributed recycling additive manufacturing (DRAM) (Cruz et al., 2020):

1 Several studies reviewed above have shown that consumers can fabricate plastic products from their own recycled waste for themselves for under 1% of the cost of purchasing them commercially. There are already millions of free and open-source 3-D printable designs for products. This provides a very strong economic incentive for people to consider DRAM. FFF plastic 3-D printers are now reasonably mature, but fused granule fabrication (FGF) and recyclebot technology is roughly 10 years behind.
2 Many of the RepRap 3-D printers are not trackable. For example, hundreds of delta-style 3-D printers (Irwin et al., 2014) and Cartesian style 3-D printers (Schelly et al., 2015) were built by students and teachers from a single university center and are not included in the AM market list. There are many other RepRap 'centers' so the total printers sold is a vast underestimate of the total number of actual 3-D printers in use.
3 Amazon, the 5th largest company in the world, now lists 3-D printer filament in its Amazon Basics section, where they sell Amazon-branded "everyday items". This indicates that distributed manufacturing with a polymer-based 3-D printer is becoming mainstream.

This research showed how even extremely complex waste polymer composites could find a path to custom 3-D printed/assisted products, which will also help to accelerate DRAM to assist in a circular economy. For this specific material additional work on the wind shield wiper material could open up other paths within DRAM to overcome the thermal and flow-related challenges of the material. Future work is also needed to investigate the applicability to windshield wiper blades used over different time periods. For example, a higher temperature syringe printer could be used, or a different kind of material feeding system may make both recyclebot operation as well as FPF printing more reliable and able to work with this example composite waste.

The primary limitation to this study is that the materials

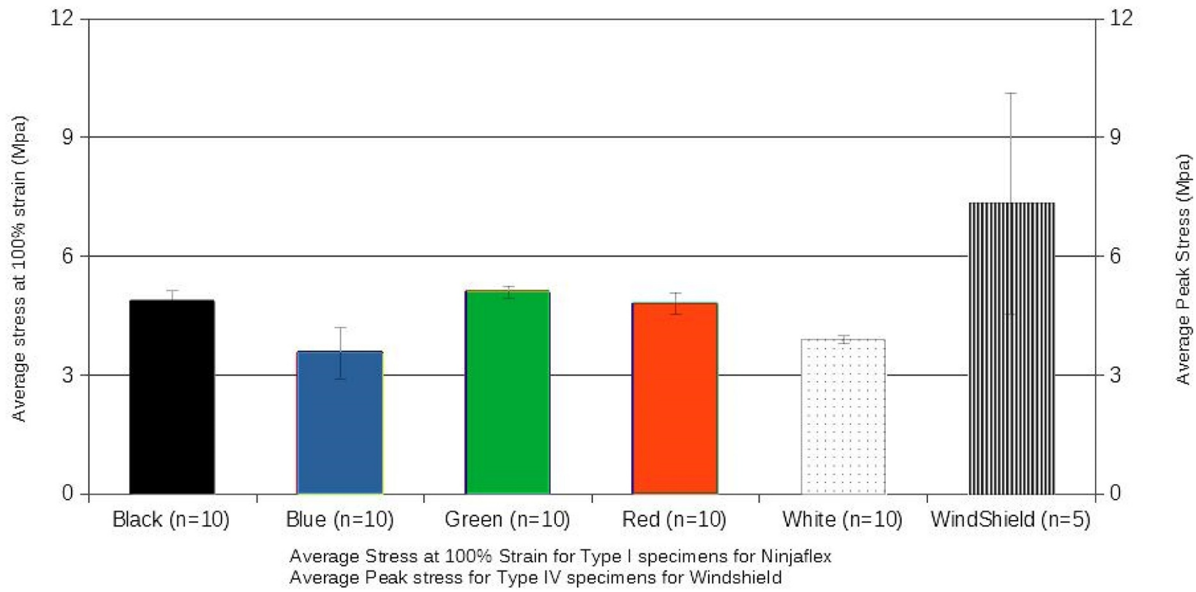

Fig. 16. Average stress at 100% strain for type I specimens for Ninjaflex average peak stress for Type IV specimens for Windshield wiper materials.

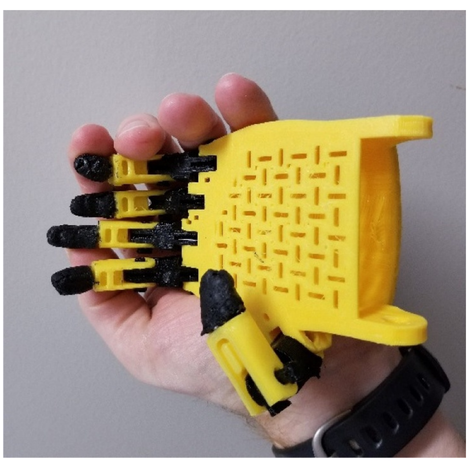

Fig. 17. 3-D printed prosthetic hand with recycled windshield wiper finger tip grips.

investigated were unknown. This, unfortunately, is the issue with all recycling materials. Even in the best-case scenarios where the major constituent of the material is known (e.g. resin code symbol 1–6) the plasticizers, additives and coloring agents are unknown. This impediment can be overcome with voluntary labeling already being adopted in parts of the 3-D printing community, but also by premium material suppliers to differentiate and demonstrate the value of their material selections (Pearce, 2018). This is far from universal, however, so there is a desperate need for a low-cost, reasonably accurate material testing device like a melt flow index (MFI) tool to support DRAM development and depolyment.

5. Conclusions

This study successfully explored the technical pathways for distributed recycling of complex polymer composites made up of windshield wiper waste for distributed manufacturing, from mechanical grinding to filament production in a recyclebot to FFF or FGF, syringe printing, or 3-D printed molds to injection molding. A successful pathway was found to convert scrap windshield wiper blades into useful, high-value, bespoke biomedical products of fingertip grips for hand prosthetic and a reflex hammer. This model of materials recycling can be used to improve the variety of solution available for the distributed recycling additive manufacturing pathway to a circular economy.

CRediT authorship contribution statement

Samantha C. Dertinger: Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Nicole Gallup:** Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **Nagendra G. Tanikella:** Formal analysis, Investigation, Data curation, Writing - review & editing, Visualization. **Marzio Grasso:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing, Visualization. **Samireh Vahid:** Validation, Formal analysis, Investigation, Data curation, Writing - review & editing, Visualization. **Peter J.S. Foot:** Validation, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Visualization. **Joshua M. Pearce:** Methodology, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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