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Technical Pathways for Distributed Recycling of Polymer Composites for Distributed Manufacturing: Windshield Wiper Blades

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Highlights

- Distributed recycling and additive manufacturing (DRAM) new pathways
- Pathways for DRAM of complex polymer composites explored
- Includes mechanical grinding and various AM methods
- DRAM can be used to improve the variety of solutions for a circular economy

Abstract

Centralized waste plastic recycling is economically challenging, yet distributed recycling and additive manufacturing (DRAM) offers a path that 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, which are a thermopolymer composite made up of a soft (flexible) and hard material. The distributed manufacturing methods ran from 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 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 prosthetic 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.

Keywords: polymer composite; recycling; additive manufacturing; distributed recycling; distributed manufacturing

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 landfilled 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 & Pearce, 2018). The open source 3-D printing community (De Jong & 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 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 & 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 every day 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 & 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).

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;c; 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), 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) 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 Figure 1. To illustrate the options for these pathways a case study is performed on windshield wiper blades, which are a thermopolymer 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 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 Figure 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.

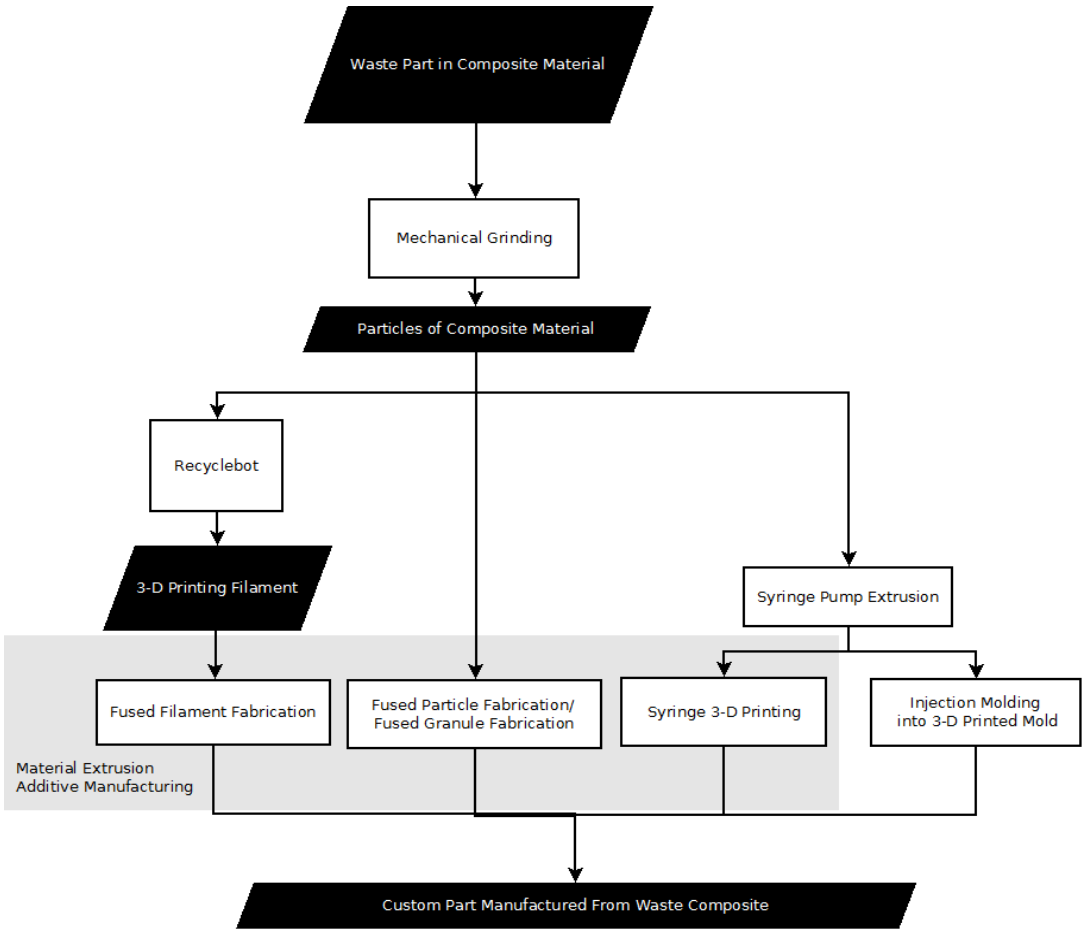


Figure 1. Technical pathways for distributed recycling of polymer composites for distributed manufacturing

2. Material and methods

2.1 Materials

Figure 2 shows the starting material of a windshield wiper blade with the two materials labeled. Material 1 is more flexible and material 2 is more rigid to the touch. Mechanically ground windshield wiper blade was provided by McDunnough Plastics, Fenton MI for $1/lb ($2.20/kg).

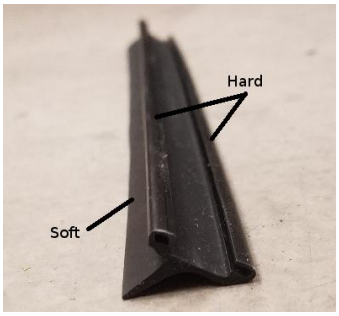


Figure 2. Image of wind shield wiper

The particle size characteristics of the starting material were quantified using digital imaging and the open source Fiji/ImageJ to determine the size distributions of the particles. Likewise 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 was determined by:

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

When using the angle of repose equation, the final answer may need to be converted between radians and degrees. Multiply the calculated answer (if in radians) by 180/π to attain the answer in degrees.

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 DSC, FTIR, TGA, and TMA tests, the material was separated into the hard and soft components and tests are performed using an amount which was enough to be representative of the sub-material behavior.

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^{o}C to 200^{o}C. The three different heating and cooling rates were 2^{o}C/min, 10^{o}C/min and 40^{o}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 wavenumber scan was set from 4000cm^{-1} to 525cm^{-1} with 4cm^{-1} resolution.

2.2.3 TGA

TGA is an experimental technique to measure mass as a function of 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 the only 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^{o}C/min) chosen from the literature (Gu et al., 2003). TGA/DSC 1 - Mettler-Toledo with STARe software system was used.

2.2.4 TMA

TMA is a technique used to predict the thermal behavior of polymers. The 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^{o}C to 250^{o}C.

2.2.5 Rheological Tests

With the rotary rheometer the viscoelastic properties of thin fluid samples up to solids can be determined as a function of shear, time, frequency and temperature. Measurements can be performed in a temperature range from -15 °C to 400 °C, in a frequency range from 10^{-5} to 100 Hz (oscillation) and in a shear rate range up to 1500 s^{-1} (rotation). The investigations were carried out with a plate-plate device (diameter 20 mm). 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"). According to Malvern (2016), the shear rate for the extrusion process should be between 1 to 100 s^{-1} and for completeness the tests were run from 0.1 to 100 s^{-1} at 180^{o}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 (Zhong & Pearce, 2018). Material was extruded at 240-270 ^{o}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, 2016). The extrusion temperature was set to 260 ^{o}C and was slowly increased after the second printing attempt was failed. 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 ˚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 3D-printed molds from ABS after failed attempts at printing large water fixtures with recycled HDPE waste in the Solomon Islands (2017; 2019). 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^{o}C.

2.4 Mechanical Properties of Manufactured Parts

Five specimens of the material were manufactured using 3-D printed polycarbonate molds following a procedure previously discussed (Reich et al., 2019) using an injection temperature of 280 ^{o}C and preparation time of approximately five minutes. The specimens were according to ASTM type IV standards adapted for 3-D printing materials (Laureto and Pearce, 2018). The specimens were then pulled until failure using a 10000 lb. load cell (Model LCF455). The strain data was captured using the crosshead extension on the Universal Testing Machine.

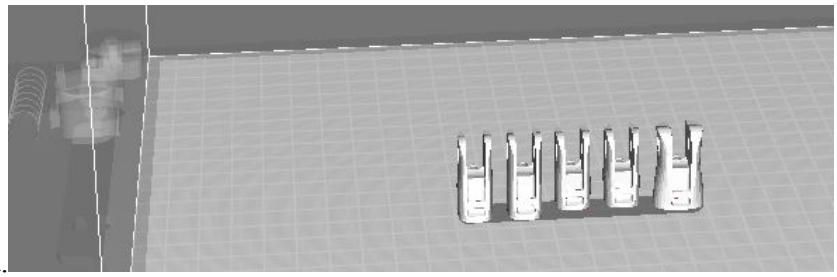
2.5 Application Demonstration

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 (Figure 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).

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

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 a 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 (Figure 4a) and tips (Figure 4b) were subsequently printed with PLA and the molds printed polycarbonate (Figure 4c), respectively. In order to use the injection molding machine the mold was secured between the metal nozzle and a flat metal piece using four socket head M4x40 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 (Figure 4a).

a.



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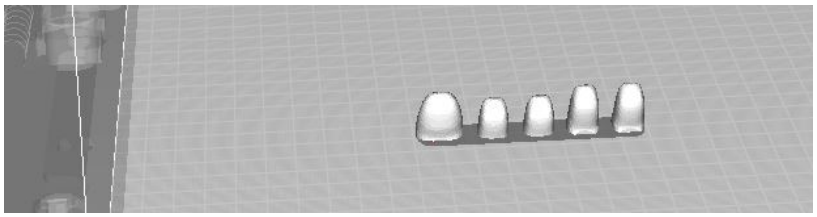

Figure 4: The (a) adapted fingers without tips and (b) the tips used to slice into molds.

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. Figure 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.

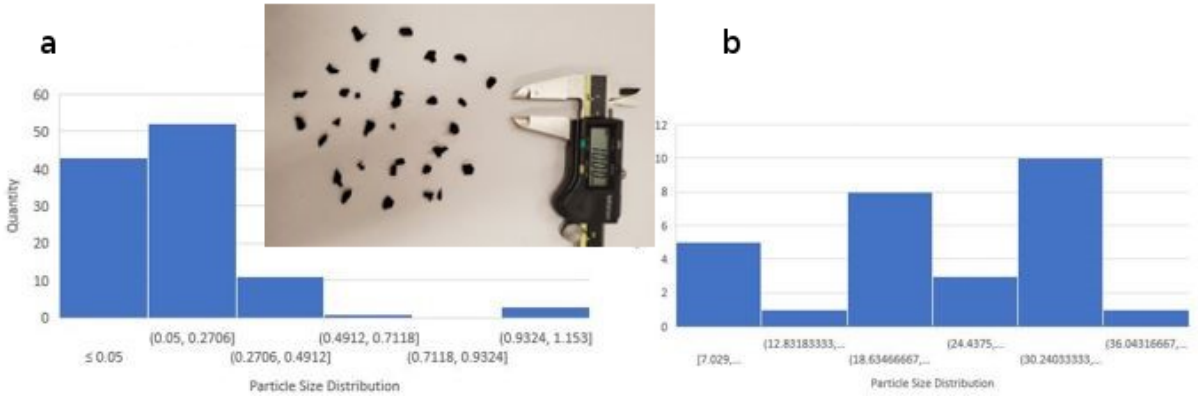

Figure 5. Particle size analysis distribution a) for particles <1.15 m^2 and b) for particles <1.15 m^2 along with inset of example analysis image.

Three trials were performed to find the angle of repose using the funnel method shown in Figure 6a and for the petri dish method shown in Figure 6b. Using the funnel method, the average calculated angle of repose was determined to be 56.2 degrees 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 degrees with a standard deviation of ± 3.2.

Figure 6. Angle of repose analysis a) pile method and b) petri dish method.

The results 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.

Figure 7 shows the thermal curves that relate to the 2°C/min scans as well as the other tests.

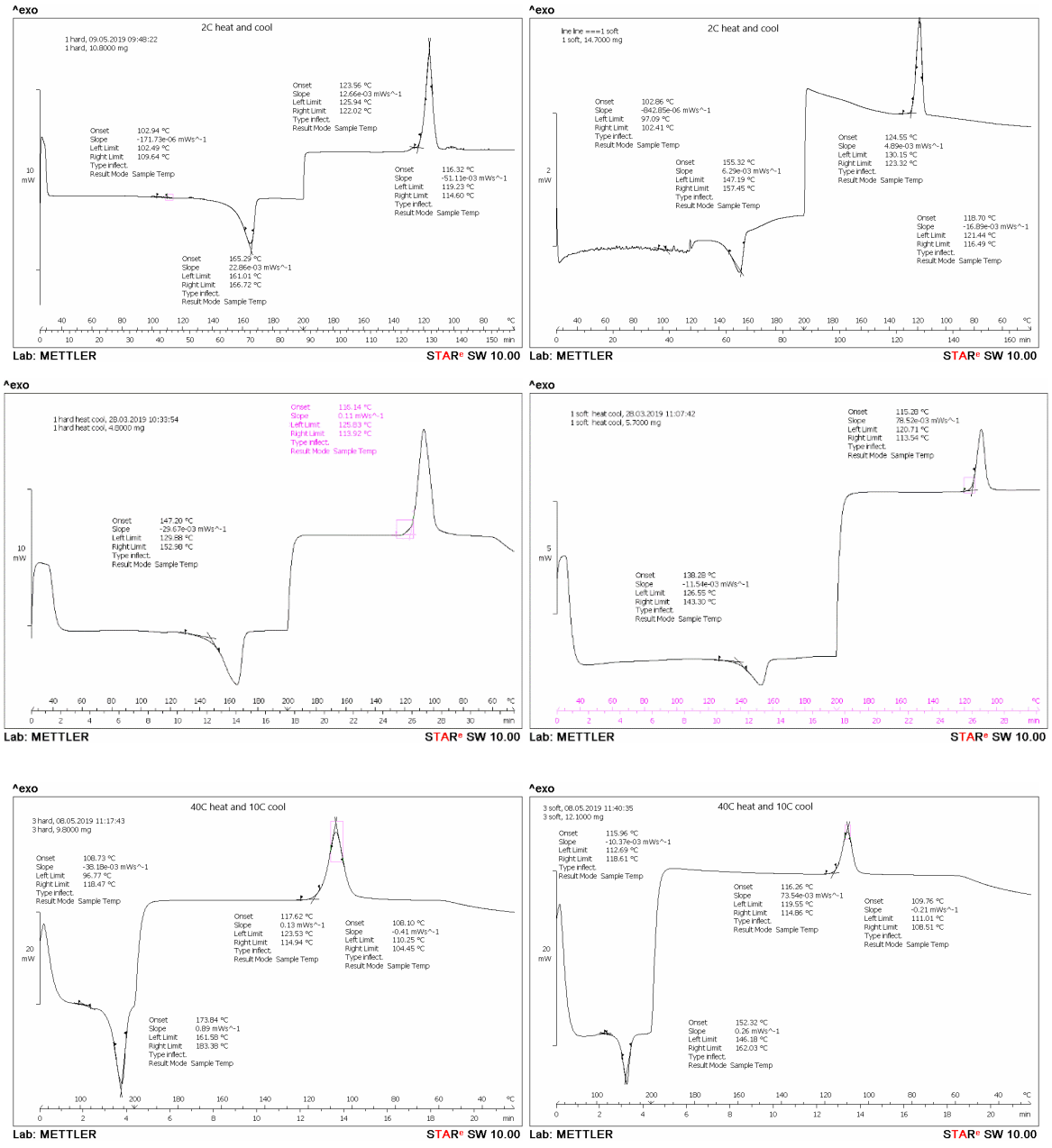

Figure 7 - Hard polymer at 2°C/min heat and cool, A-2: Soft polymer at 2 °C/min heat and cool. B-1: Hard polymer at 10 °C/min heat and cool, B-2: Soft polymer at 10 °C/min heat and cool. C-

1: Hard polymer at 40 ^{o}C/min heat and 10 ^{o}C/min cool, C-2: Soft polymer at 40 ^{o}C/min heat and cool.

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

Table 1 - Melting and crystallisation temperatures of hard polymer

	Melting Temperature (Tm)	*Crystallisation Temperature (Tc)*
2^{0}C/min Heat and cool	165.29	123.56
10 ^{0}C/min Heat and cool	165.55	115.75
40^{0}C/min Heat and 10 ^{0}C cool	177.32	115.41

Table 2 - Melting and crystallisation temperatures of soft polymer.

	Melting Temperature (Tm)	*Crystallisation Temperature (Tc)*
2^{0}C/min Heat and cool	154.90	125.46
10 ^{0}C/min Heat and cool	153.10	115.6
40^{0}C/min Heat and 10 ^{0}C cool	154.20	115.34

The results for melting and crystallisation temperature values of the hard and soft polymer are reported in Tables 1 and 2, respectively. The results show similar trends and similar values, indicating that the two sub-materials have similar composition, however there is roughly a greater than ten degree 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^{o}C/min and 10^{o}C/min rate does not change much and it increases drastically at 40^{o}C/min heating rate. For both sub-materials, the crystallisation temperature (T_c) is higher at 2^{o}C/min compared to the one for 10^{o}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.

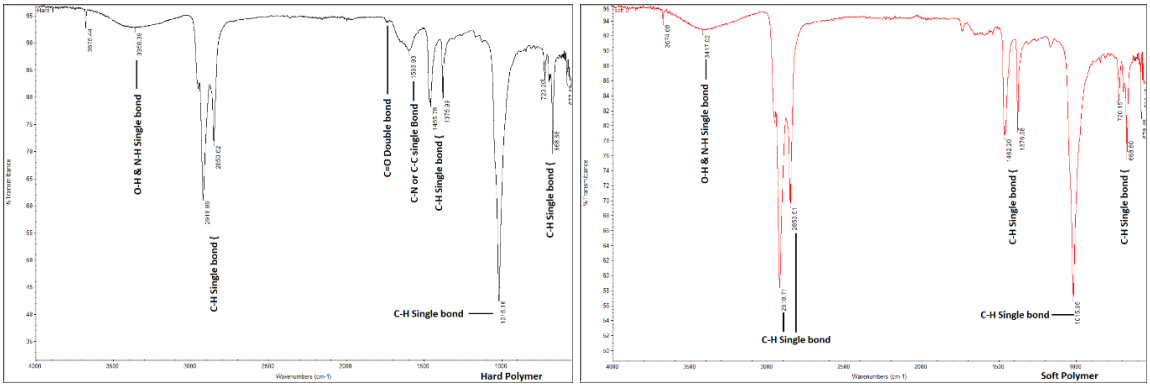

Figure 8 - Infrared spectrum of Hard polymer (left) and Soft Polymer (Right).

The two polymers show similar infrared spectra with the only difference being the peak at 1593.3 cm^{-1} observed in the hard polymer (Figure 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, 2850, 1455, 1375, 1015, 720 and 668cm^{-1} which are all indicating C-H stretching or bending vibrations.

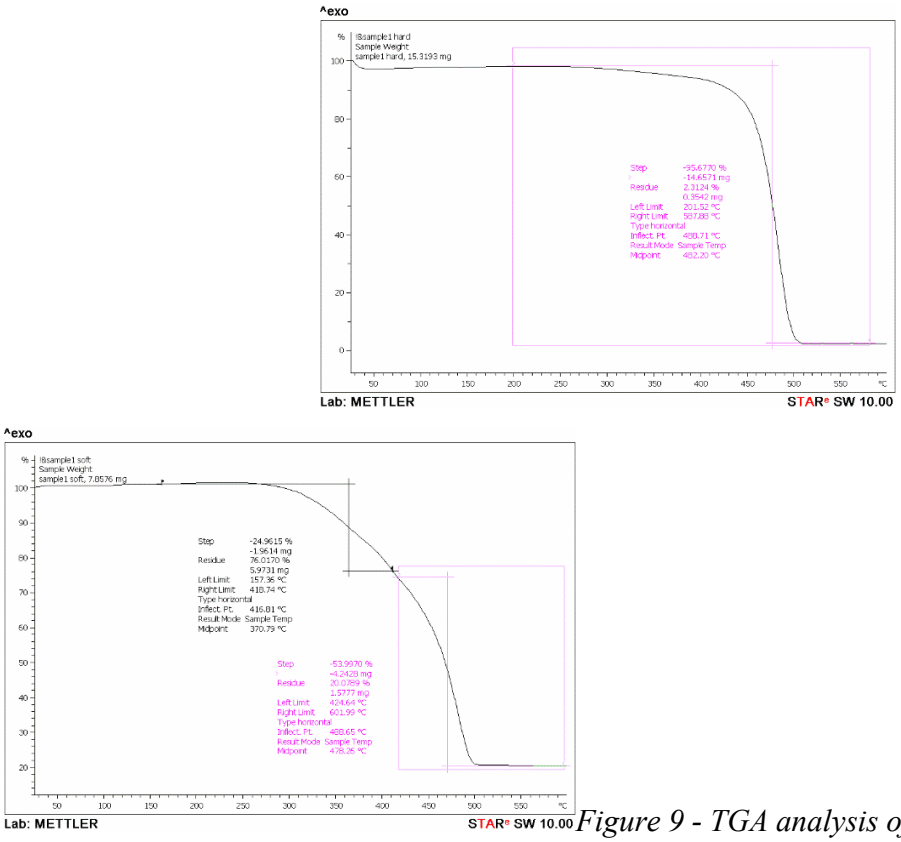

Figure 9 - TGA analysis of hard polymer (left) and soft polymer (right).

Figure 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^{o}C and the polymer is stable up to this temperature. At the end of the test, there is only 2% carbon material left.

The soft polymer decomposes in two stages. The first stage is from 250^{o}C to 420^{o}C, during which it loses approximately 25%, and the second stage is from 420^{o}C to 500^{o}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 in the waste from wind shield wipers.

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

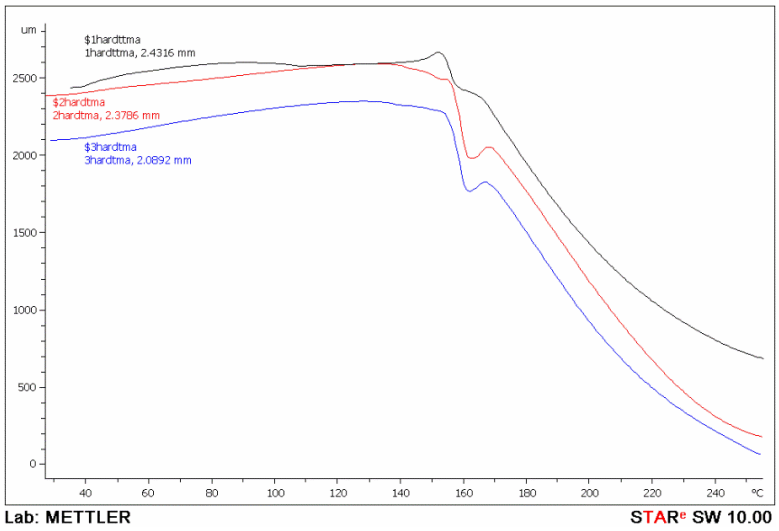

Figure 10 - TMA analysis results of hard polymer.

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 ~ 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.

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

	Percentage Shrinkage	
Hard Polymer	**170 °C**	**180 °C**
Sample 1	7.4 %	19.2 %
Sample 2	13 %	30.1 %
Sample 3	13.5 %	28.4 %

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

(Figure 10). 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.

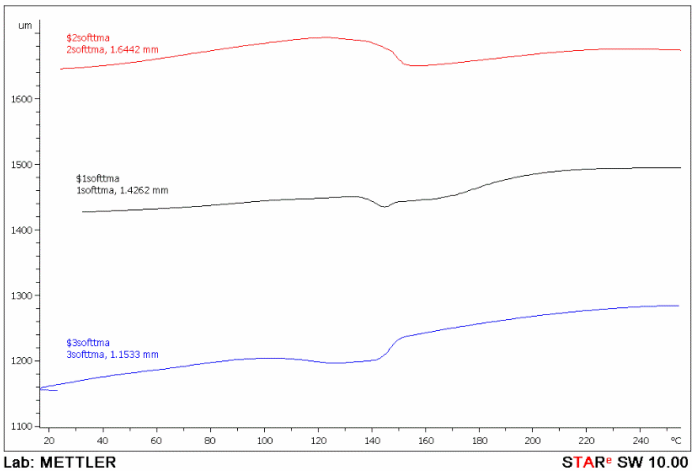

Figure 11 - TMA analysis results of soft polymer.

For the soft polymer, the following temperature values were measured: Glass transition temperature T_g ~ 130°C; crystallization temperature T_c ~ 140°C; and melting temperature T_m ~ 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.

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

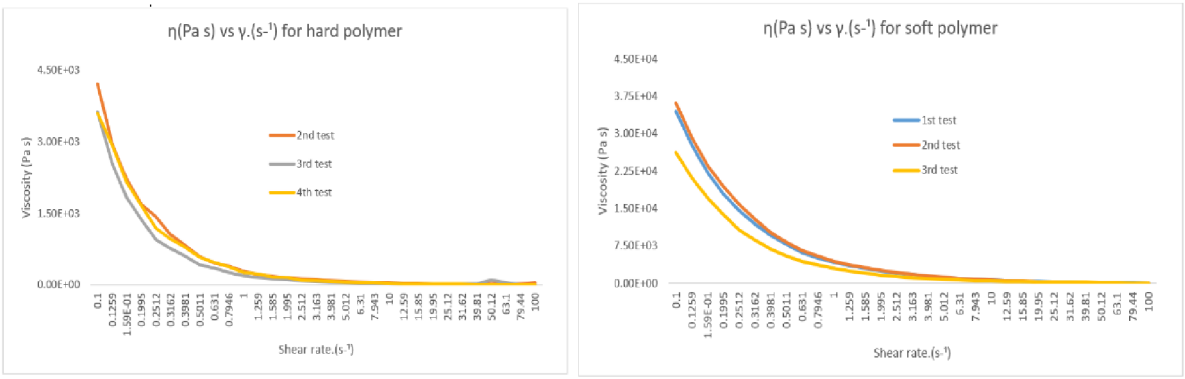

Figure 12 - Viscosity for hard and soft polymer vs shear rate.

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 36200 Pa·s to 26300 Pa·s for 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 & Rudolph, 2014).

In the most common path for 3-D printing (FFF) shown in Figure 1, the vertical recyclebot was able to successfully make filament as seen in Figure 13.

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

However, although 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 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 PC mold, which is shown in Figure 14.

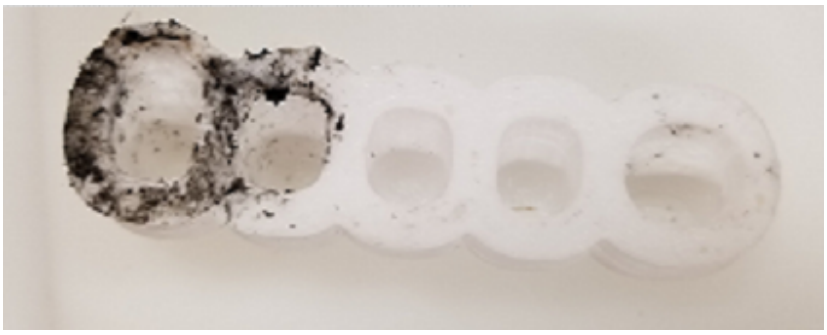

Figure 14. The polycarbonate printed finger tip molds after use.

As can be seen in Figure 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 7.34MPa with a standard deviation of 2.785. The average strain during breaking was 122.13%.

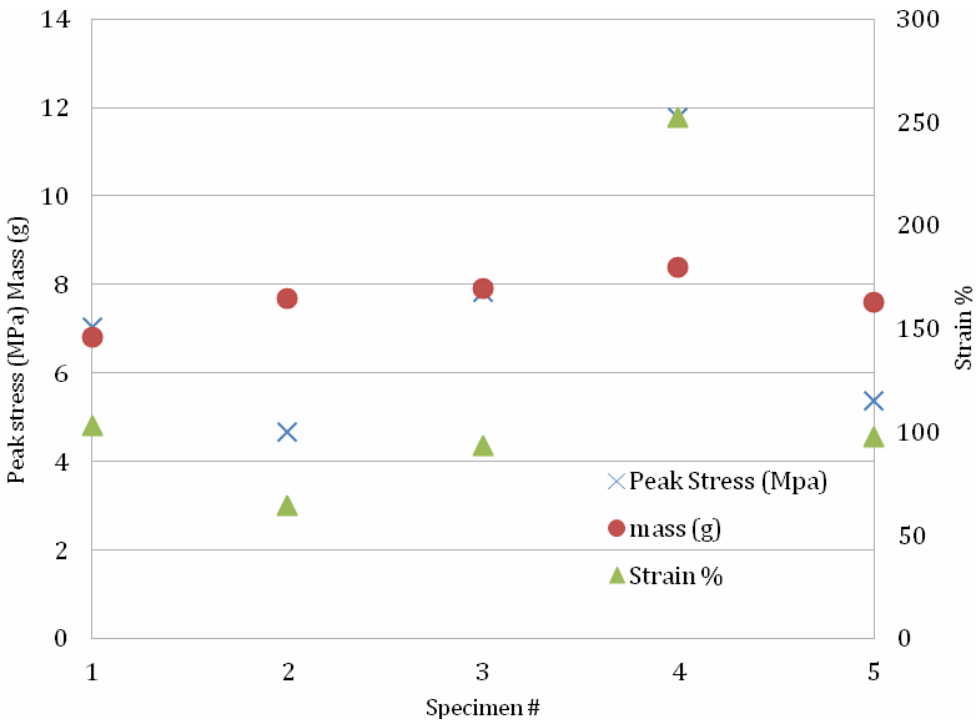

Figure 15. Peak stress (MPa) and mass (g) on left axis and percent strain on right axis of tensile bar tests made with the wind shield wiper material.

The material can be compared to a commercial flexible 3-D printing material. Figure 16 shows this comparison between Ninjaflex filament that was 3D printed according to ASTM 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. 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.

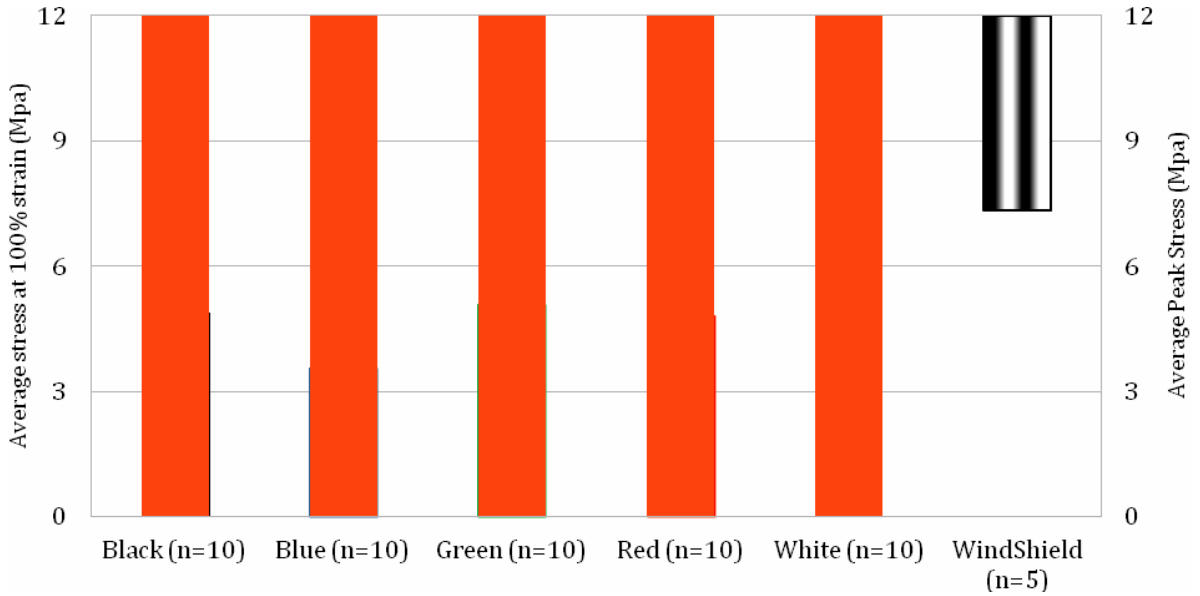

Figure 16. Average stress at 100 % stra

in for type I specimens for Ninjaflex average peak stress for Type IV specimens for Windshield wipe materials.

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 (Figure 17).

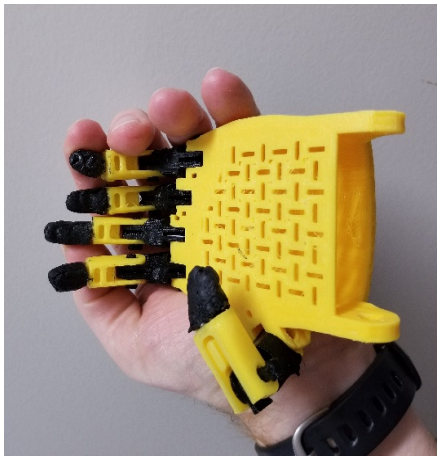

Figure 17. 3-D printed prosthetic hand with recycled windshield wiper finger tip grips.

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 (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 thermopolymer-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. 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.

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.

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