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Mechanical properties evaluation of recycled high density polyethylene via additive manufacturing

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Abstract

The recycling of plastic waste has become increasingly important due to the negative impact of plastic on the environment. Additive manufacturing, also known as 3D printing, offers a promising solution for utilizing recycled plastics in the production of new parts. Due to increased demand and the production of polymers, recycling of plastic materials is highly sought nowadays. The thermo mechanical processes used to recycle these materials change their mechanical behavior. The current study focuses on the recycling of high-density polyethylene (HDPE), one of the most recycled materials in the world, to be recycled for use in additive manufacturing. Experimental testing and evaluation of the impact and tensile properties of fused filament fabrication (FFF) specimens made from virgin and recycled materials. This study reveals that the mechanical properties of the recycled HDPE polymer were generally improved over several recycling steps, making HDPE recycling a viable option for circular use. Moreover, repetitions two through five exhibited the best overall mechanical behavior, demonstrating that HDPE polymer recycling has a significant influence apart from the environmental one.

*Keywords:*Additive nanufacturing, 3D printing, recycling, HDPE, material characterization

Nomenclature

PET	Polyethylene terephthalate
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
PS	Polystyrene
FDM	Fused deposition modeling
PLA	Polylactic acid
ABS	Acrylonitrile butadiene styrene
FFF	Fused filament fabrication
PP	Polypropylene

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1. Introduction

The demand for lightweight and durable parts has resulted in the production of around 359 million tonnes of plastic items globally in 2019. However, poor waste management has caused nine billion tonnes of plastic waste to end up in the environment each year [1, 2]. Polymer resins such as PET, HDPE, LDPE, and PS are used to manufacture the majority of plastic parts accessible worldwide. According to the literature, HDPE garbage accounted for 22% of global waste in 2019, producing 51.33 million tonnes of plastic. When comparing HDPE manufacturing to PET production, PET wastes accounted for around 11% of total waste generated (41.56 million tonnes). Polyolefins are primarily derived from oil and natural gas through the polymerization of ethylene and propylene. Because of their versatility, they are now one of the most widely used plastics. Automotive part (PP), electrical components, houseware, industrial wrappings, gas pipes (HDPE), bags, toys, and containers (LDPE) are the most common thermoplastics used internationally [3]. HDPE plastic, as one of the most versatile materials available, is also utilized in a variety of industrial applications to replace heavy parts with lighter ones that can handle comparable stresses while offering corrosion resistance, rigid strength, and environmental friendliness. HDPE is also appropriate for sustainable and affordable manufacturing due to its high recyclability and cost-effectiveness [4].

Fused Filament fabrication (FFF) or 3D printing is gaining popularity in modern technology due to less waste produced. FFF also known as FDM, is a 3D printing technology that uses a continuous thermoplastic filament [5]. The "ink" (filaments) cost for FFF 3D printers ranges from 19 to 80 USD per kilogram, which is a high price. High-impact polystyrene, nylon, PLA, and ABS are the most frequently used plastics for FFF [6]. Most commercial filaments, except PLA, a bio-polymer made of corn starch, are produced from crude oil and are not recyclable. For example, nylon, PLA, and ABS all lies in resin identification code 7, which is associated with "others" that are not recyclable [7].

Several studies are available on the mechanical properties of FFF specimens in 3D printing of thermoplastics and recycled thermoplastics [8, 9]. However, studies on recycled additive manufacturing materials, in general, are minimal [10]. A Cradle-to-Cradle recycling and reclamation framework for FFF 3D printing has been proposed by Chong et al. [11] that connects five key components: plastic recycling, pretreatment, extrusion to filaments, 3D printing, and users. A distributed recycling platform with an international recycling code system for 3D-printed products is recommended. Baechler et al. [12] demonstrated high-value waste polymer recycling through the successful extrusion of filaments from RecycleBot utilizing HDPE. Haruna et al. [13] researched and found the solution that the recycled HDPE filament is suitable for 3D printing. However, some mechanical properties of recycled HDPE filament can be changed for better results, like melt Index, tensile strength, Young modulus, and strain. Jason et al. [14] determined the feasibility of extruding recyclable plastic into usable filament to create a sustainable technology for 3D printing. Moreover, an issue of low intrinsic viscosity has been occurring due to the high speed of their extruder, resulting in increased shear stress on the plastic during the extrusion process. Recycling of waste plastic to create 3D printing filaments is the focus of some organizations, including Plastic Bank, Perpetual Plastics Project, and Project Seafood. Despite the community's relentless efforts, only a few studies have been done on 3D printing with recovered plastic trash. Charles et al. [15] used the Taguchi methodology to assess the tensile strength, three-point bending strength, and impact strength of test objects created from three-dimensional (3D) printed PLA and recycled PLA. The optimal parameters were layer thickness (0.25 mm), occupancy rate (70%), and filament type (PLA). The study demonstrates that Re-PLA filament can be used to create 3DP, and using recycled filament emphasizes the significance of environmental awareness. Oussai et al. [16] analyzed the mechanical properties of two different kinds of printed PET tensile test specimens. Both new and used PET is used to create the materials. All forty test samples from the two forms of PET were assessed. Comparisons were made between the test samples' elongation at break, stress-strain curve changes, and tensile strength values. The recycled filament's hardness decreased to 6 percent, but its tensile strength and shear strength increased to 14.7 and 2.8 percent, respectively. The tensile modulus elasticity, however, did not alter. The ideal printing setting for PET is 100% recycled since at 40% recycled PET, its elongation can only reach 3.12 % while its tensile strength can reach up to 43.15 MPa.

As a result, there is currently no extensive literature on the mechanical properties of HDPE via 3D printing. The current study looks into the viability of recycled HDPE as a filament material to determine the impact of recycling on the mechanical strength of the final specimens. It provides processes for preparation and analysis, as well as printing suggestions utilizing recycled HDPE. This work will serve as a foundation for future research on using recycled plastic waste in 3D printing techniques to establish a greener 3D printing sector. The overall purpose of this study was to demonstrate that HDPE polymer can be successfully recycled multiple times to be used as a material for constructing parts with FFF 3D printing. To that end, the influence of 3D printing on the mechanical properties of recycled HDPE specimens was investigated. Mechanical testing (tension and impact) was utilized to determine the impacts of degradation processes on the mechanical characteristics of the specimens. The HDPE polymer characteristics improved up to the fifth recycling phase, indicating that the recycling process did not affect the HDPE polymer. The HDPE polymer characteristics began to decline after the sixth recycling step.

2. Material and Methods

2.1 Material

The plastic HDPE bottles were grinded to prepare the collected waste of HDPE plastic. The grinding of HDPE plastic buildup occurs in three steps. The first step is to collect the plastic waste; the second is to dry the bottles; and the third is to grind and shred the bottles to a specific particle size. The HDPE was in fine powder form. The identical raw material was used throughout the experiment. The thermo physical and mechanical properties of HDPE plastic are below in Table 1 and Table 2.

Table 1. HDPE polymer thermo-physical properties

Properties	**Unit**	**values**
Melting point	ºC	127-134
Density	g/l	0.954-0.962
Heat deflection temperature	ºC	65-76
Thermal conductivity	W/mK	0.34-0.48
Hardness	-	54-66

Table 2. Mechanical properties of HDPE polymer at 23 °C

Property	**Unit**	**Value**
Tensile strength yield at 23 ºC	MPa	22.5-28.0
Tensile strength break at 23 ºC	MPa	29.0-32.5
Elongation, yield	%	8-17
Tensile modulus at 23 ºC	MPa	905-1540
Flexural modulus	MPa	980-1380
Izod notched	kj/m^2	70-160
Izod unnotched	kj/m^2	-

2.2 Method

2.2.1 Recycling simulation and experimental course parameters

Initially, virgin HDPE filament was produced by extrusion using HDPE powder. The filament was thoroughly examined for quality control to ensure a uniform diameter of 1.75 mm. Part of the initial HDPE filament was used to make FFF specimens [17-19]. Specimens were thoroughly inspected and analyzed regarding dimensional stability and physical qualities (such as color, surface quality, and structural flaws) [20]. Tensile and impact tests were performed following international standards to evaluate the mechanical properties of 3D-printed virgin HDPE specimens. Throughout the current study, the extruder's working temperature was adjusted to 230 ºC. This working temperature was determined experimentally with an extrusion device producing a continuous 1.75 mm diameter filament with fine surface quality while maintaining a constant and uninterrupted extrusion flow. The filament diameter tolerances are determined by the extruder vendor, who specifies 1.75 ± 0.04 mm. Fused filament fabrication specimens were made for the experimental procedures and testing, and the specimens were evaluated to determine their physical/mechanical properties at a room temperature of 23 ºC.

Plastic recycling was carried out through the crusher developed at the Department of Mechanical Engineering, International Islamic University, Pakistan as shown in Fig 1. The recycling capacity of the plastic crusher is 50 kg/hr. plastic crushing includes plastic waste, cleaning, drying, and crushing. The plastic waste was bought from a local market based on its resin identification code. After that, this plastic was cleaned manually with detergent to contain no dirt and debris particles. Once thoroughly washed, it was placed in an open environment for 5 to 6 hours directly under the sunlight for drying so that all the moisture from the waste HDPE should be removed. Once it dried, it was then crushed with a Plastic crusher machine, and we obtained small, approximately equal size crushed plastic. The main component of the extrusion machine is the screw and barrel mechanism.

The Helix angle of a screw in an extrusion machine is calculated through Equation 1.

$$\text{Helix Angle} = \tan\varphi = \frac{L}{\pi D} \tag{1}$$

Similarly, the compression ratio of screw as shown in Equation 2

$$\text{Compression Ratio} = \frac{\text{Channel Depth at feed Zone}}{\text{Channel Depth at Metering Zone}} \tag{2}$$

The compression ratio is 3:1 Feed Zone = 50% of total length, Compression zone = 25% of total length, and Metering Zone = 25% of total length. Another important factor in the screw and barrel mechanism is the shear rate. Shear rate plays a vital role in pushing and melting plastic. Shear rates in the screw channel and at dia are calculated through Equation 3 and Equation 4.

$$\text{Shear Rate in screw channel } (\gamma) = \frac{\pi D N}{60\, h} \tag{3}$$

$$\text{Shear Rate at die } (\gamma) = \frac{4\, Q}{\pi R^3} \tag{4}$$

The whole process of waste-to-filament production includes five steps: plastic waste, shredding, extrusion, quenching, and filament. Before the extrusion process, the crushed plastic was placed in an open environment for drying so that all the moisture content would vanish before passing through the extrusion machine. After 7-8 hours of drying, the crushed plastic was fed into the hopper, and the band heaters were turned on. Four band heaters are installed on the screw. The capacity of one band heater is 800 W. Each band heater is placed at an equal distance. The melting temperature of HDPE polymer is 130 ºC, so the temperature is set to 160 ºC. The specification of the extrusion machine is shown in Table 3.

Table 3. Extrusion Machine specifications

Barrel	
Length	452 mm
Inner diameter	35 mm
Outer diameter	77.3 mm
Flange	
Length	28.5 mm
Bolt Diameter	15 mm
Bolt Washer Outer Diameter	16.4 mm
Screw	
Total Shaft Length	655 mm
Screw Length	452 mm
Screw Diameter approx.	35 mm
No. of Threads	13
Key Length	51 mm
Key Width	16 mm
Key Height	8.1 mm
Channel Depth	6 mm
Channel Width	22.8 mm
Screw Pitch	39 mm

Once the plastic start melting, we turn on the screw, whose speed can be controlled through a Variable Frequency Drive (VFD). After that, the filament is passed through water, where it gets quenched, and the filament is passed through the roller, and finally, it is collected on a spool. The whole mechanism is shown in Fig 1.

Fig. 1 Experimental set-up

2.2.2 Tensile Specimens Fabrication and Testing

Tensile specimens were created following the American Society for Testing and Materials (ASTM) D638-02a international standard. Tensile tests were carried out and set up in tension mode with standardized grips. The tensile test machine chuck was adjusted to a 10 mm/min speed for testing following international standards.

2.2.3 Impact Specimens Fabrication and Testing Part

The impact specimens were built following the ASTM D6110-04 standard, measuring 90 mm in length, 10 mm in width, and 12 mm in thickness. The samples were all created with the impact notch from the ASTM D6110-04 standard. For each experiment, the apparatus's hammer was released from the same height to calculate each specimen's impact energy. The results were test through Charpy impact test experimental set up.

3. Results and Discussion

3.1 Tensile Test

The tensile mechanical behavior results of recycled HDPE are shown in Fig 2. The mechanical properties of virgin HDPE polymer have been intensively examined and absorbed in the literature. Because of the low printability of the HDPE material, there is no comprehensive research on the mechanical properties of 3D printed HDPE specimens. The current study results for recycled HDPE are in good agreement with the literature [21, 22]. The overall results on the mechanical characteristics of virgin and recycled HDPE revealed an increase in mechanical properties until the fifth recycling step, demonstrating a solid reason to recycle HDPE, even though FFF, as an end manufacturing process option, exists. According to the findings of this study, each recycled course enhanced the mechanical strength of the virgin HDPE material. More specifically, while comparing recycling steps one to five, it was shown that there was a 25.33% improvement in tensile strength. Between the first and fifth recycling steps, the tensile modulus of elasticity increased by 25.26%. However, at sixth recycling step the tensile strength decrease significantly because at sixth recycling step the recycle material is more brittle. According to the literature, virgin HDPE injection molded specimens have a tensile strength of 28.2 MPa, while recycled specimens have no difference in tensile strength.

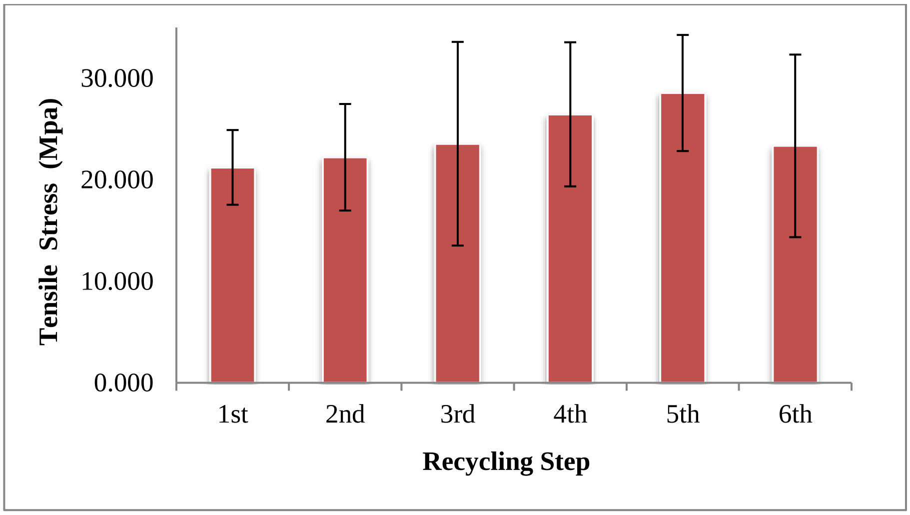

Fig 2. Recycling step vs tensile stress

3.2 Impact Test

The results of impact testing are as shown in Fig 3 in which the average value and deviation of the calculated impact strength for all the experiments are presented. When comparing the first and second recycling stages, impact strength experiments revealed a substantial increase of 53.93%. There is no literature on the impact strength of HDPE FFF specimens or recycled ones. When comparing the first and third recycling steps, the micro-hardness Vickers values showed a 29.88% increase. Changes in hardness can be directly attributed to changes in crystallinity.

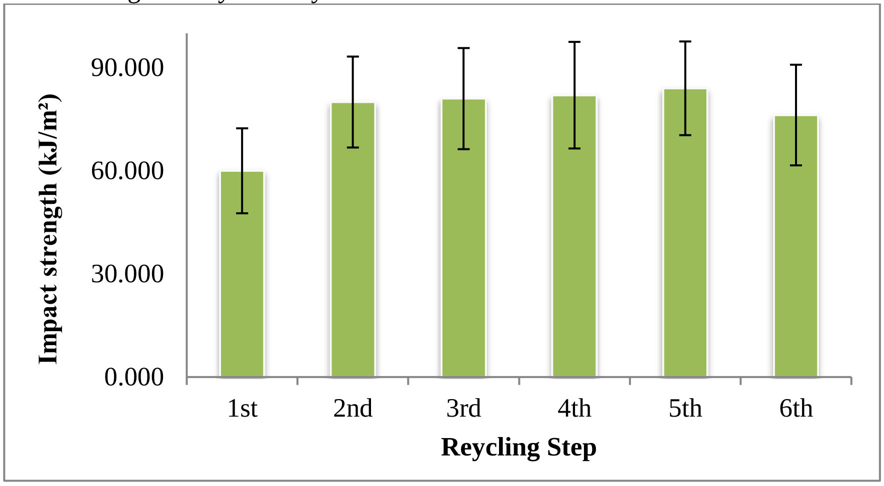

Fig 3. Recycling step vs impact strength

4. Conclusion

This study examined the effect of mechanical treatment during the recycling process on the mechanical characteristics of HDPE polymer after a specific number of recycling steps. Six recycling stages were completed, and FFF specimens' tensile and impact properties from each recycling step were determined. The results show that the recycled HDPE polymer's overall mechanical behavior improves after a number of recycling steps, making HDPE a promising polymer for cyclical use. The optimal overall mechanical behavior was discovered between the second and fifth recycling steps, indicating the considerable positive influence of HDPE polymer recycling and circular use. The recycling processes changed the mechanical characteristics of HDPE polymer, resulting in an average 24% increase in all mechanical properties evaluated herein between the second and fifth recycling courses. In contrast, the polymer appeared to be gradually deteriorating following the sixth recycling step.

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