Resources, Conservation & Recycling 192 (2023) 106925

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Recycling of polyethylene: Tribology assessment

Harsha Raghuram [*], Julia Roitner, Mitchell P. Jones, Vasiliki-Maria Archodoulaki

Institute of Materials Science and Technology, Faculty of Mechanical and Industrial Engineering, TU Wien, Grumpendorferstrasse 7, Objekt 8, Vienna, 1060 Austria

ARTICLE INFO

Keywords:
High-density polyethylene
Design from recycling
Upcycling
Tribology

ABSTRACT

Use of recycled polymers is heavily application restricted based on mechanical-property-dependant requirements, which often result in downcycling into low-value products. Exploration of new applications for recycled polymers, and more ambitiously upcycling, falls to clever design, understanding of application-specific requirements, and differences between various grades of the same polymer. This constitutes a shift from an individual component exposed to external influences, to a component within a system acted upon by other known components and results in different design requirements. The higher-value system-specific opportunities of various reprocessed PE-HDs for use in the field of tribology were assessed. Reprocessed PE-HD exhibits differences of up to 20% in melt flow and mechanical properties compared to virgin PE-HD and may not be suitable for many engineering applications. It is, however, comparable to PE-UHMW based on tribological system-specific requirements alone (coefficient of friction < 0.1). Use of reprocessed PE-HD in this field constitutes upcycling due to the high value of the resulting products and the expansion of recycled material to new applications. Such expansion will be critical to meet ambitious new EU targets and legislation on use of recycled material, with existing applications for recycled materials highly limited and already saturated.

1. Introduction

The importance of polymer recycling to the environmental sustainability of the Earth seems indisputable, with governments and communities alike advocating its adoption and expansion. And yet, recycled polymers remain greatly underutilised, with their use restricted to just 8.5% of new products (Plastics Europe, 2022). The underutilisation of recycled polymers is typically due to their sometimes-inferior mechanical properties or reduced processability, which is in turn caused by polymer or inorganic contamination attributable to flawed sorting processes or degradation attributable to reprocessing. These deficiencies are well-known and characterised (Karaagac et al., 2021; Oblak et al., 2015; Ragaert et al., 2020; Schweighuber et al., 2021) and result in a restricted scope of use for recycled polymers across limited applications. Relevant academic literature and patents documenting change in material properties as a result of recycling are presented in Table 1.

Mechanical properties are typically used to assess the ability of a recycled polymer to meet application-specific requirements and the viability of a polymer's subsequent adoption for certain applications. This approach has been exhausted over time and the result: usually the downcycling of recycled polymers into low-value products (Fig. 1). 86% of all use of recycled polymers is in just three applications: building and construction (45%), packaging (30%) and agriculture, farming and gardening (11%) (Plastics Europe, 2022). Opportunities for innovation in new applications for recycled polymers, and more ambitiously upcycling, fall to less well characterised fields and acknowledgement of the differences between various grades of the same polymer. It is such fields that must be investigated if the use of recycled polymers is to be expanded beyond their traditional limited applications.

As an example, tribology, the study of friction and wear, is highly system specific i.e., unlike material properties, such as mechanical properties (which are constant and unchanging for a given specimen of fixed composition and environment), friction and wear will vary based on the interacting constituents e.g., surfaces, interfacial effects and similar, even under constant environmental and test conditions (Stachowiak and Batchelor, 2005). This means that while a recycled polymer may not necessarily meet the requirements of an application as an individual component subjected to external influences, it could be suitable for use within a system in which loads are generated through interactions with other system components. The effect of recycling on the suitability of a material for tribological applications is also different from that associated with a material's suitability for others: Changes in the properties of surfaces are important, while degradation of bulk material properties that may render a material unsuitable for

---

[*] Corresponding author.
E-mail address: harsha.raghuram@tuwien.ac.at (H. Raghuram).

https://doi.org/10.1016/j.resconrec.2023.106925
Received 31 October 2022; Received in revised form 27 January 2023; Accepted 12 February 2023

Table 1
Overview of academic literature (1, 10, 50, 100 × reprocessed) and patents for recycled PE-HD (rPE-HD) and household solid waste (HSW) comparing weight-average molecular weight (M_W), mass-flow rate (*MFR*), crystallinity (%*X*), Young's modulus (*E*), yield strength (σ_Y) and elongation at break (ε_b) before and after recycling.

Recycling	Virgin M_W (kg/mol)	*MFR* (g/10 min)	%*X* (%)	*E* (MPa)	σ_Y (MPa)	ε_b (%)	Reprocessed M_W (kg/mol)	*MFR* (g/10 min)	%*X* (%)	*E* (MPa)	σ_Y (MPa)	ε_b (%)	Reference
Academic literature													
1 × reprocessed	–	–	58	–	20–25	–	–	–	58	–	20–25	–	(Chrysafi et al., 2022)
10 × reprocessed	–	6.8	40	720	26	75	–	5.2	26	769	27	54	(Mendes et al., 2011)
50 × reprocessed	158	0.2	44	280	24	70	120	0.5	44	270	17	300	(Benoit et al., 2017)
100 × reprocessed	190	7.5	72	–	–	–	90	0.1	62	–	–	–	(Oblak et al., 2015)
Patents													
HSW	–	–	–	–	–	–	>10 (Mw/Mn)	0.1–4	–	–	–	–	(Durane and Mlinaric, 2017)
HSW	–	–	–	–	–	–	–	0.5–1.5	–	500–1000	22–26	–	(Manica, 2013)
rPE-HD	–	–	–	–	–	–	–	–	–	–	10–12	–	(Shaneour, 1995)

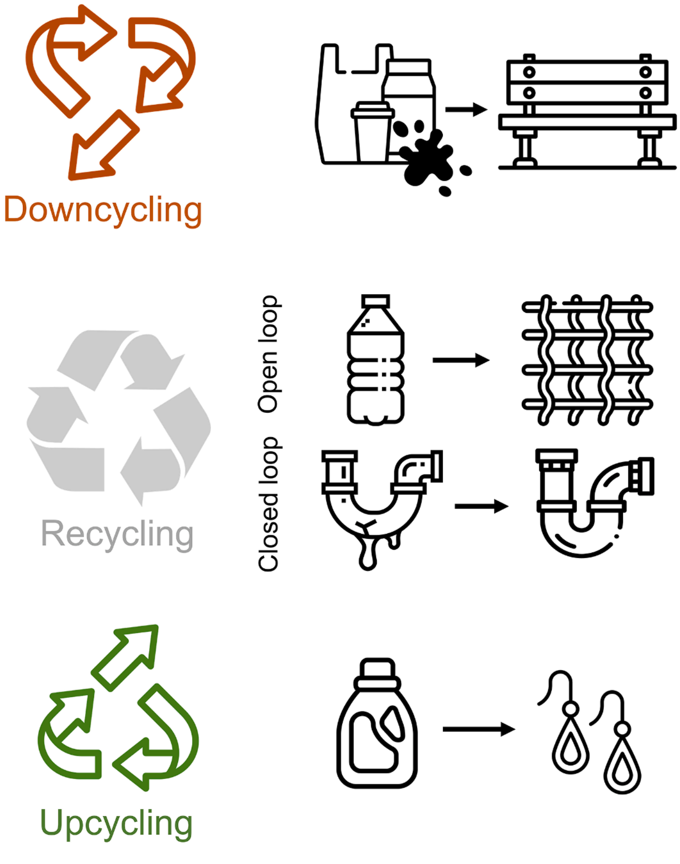

Fig. 1. Waste management of plastics through downcycling (conversion of plastic waste into products with a lower value than that of the original product e.g., conversion of contaminated packaging into park benches or black waste bins where the required stiffness is derived from the wall thickness); recycling (conversion of plastic waste into products with a similar value to the original product) using open (different end product to original product e.g., a bottle is reprocessed into textiles) or closed loops (same end product e.g., a pipe is reprocessed into a pipe); and upcycling (conversion of plastic waste into a product with a higher value than that of the original product e.g., bottle cap is made into a designer object such as jewellery).

engineering applications likely affect its suitability for tribology to a lesser extent. Applications associated with tribology, such as bearings, are also usually considerably higher value than traditional applications of recycled polymers meaning that a system-based design methodology allowing for the use of this material in such applications provides increases in the value of the recycled material (upcycling). A material's suitability to meet tribological applications can be investigated using sliding wear and scratch tests.

We initially performed a base characterisation of the processibility and mechanical properties of three different grades of reprocessed high-density polyethylene (PE-HD), one of the most widely recycled polyolefins, to establish their property envelope and associated compatibility with traditional scope of use. Samples had low and high molar masses and were intended for three different applications (packaging, pipes and caps/closures). However, in contrast to traditional design processes, we then considered higher-value system-specific opportunities for reuse (upcycling) in the field of tribology. To demonstrate this, the friction and wear properties of PE-HD and ultra-high-molecular-weight polyethylene (PE-UHMW) were assessed and compared and scratch tests performed on virgin and reprocessed PE-HD.

2. Materials and methods

2.1. Materials

Three different grades of PE-HD were selected based on their intended application: packaging, pipes and caps/closures. Borstar FB3450 "HD-Pack" (packaging), BorSafe HE3490 LS-H "HD-Pipe" (pipes) and BorPure MB6561 "HD-Cap" (caps/closures) were supplied as granulate by Borealis AG (Vienna, Austria) (Table 2). HD-Pack contained anti-oxidant additives and HD-Pipe contained pigments and UV stabilisers according to the manufacturer's data sheet. PE-UHMW GUR 1050 grade was also acquired from Ticona (Oberhausen, Germany) in the form of cylinders and included as a reference material for tribology tests. All materials were used as received.

2.2. Reprocessing of the PE-HD samples

PE-HD granulate was reprocessed to simulate the recycling cycle. The scope of the study was limited to the effects of reprocessing on the mechanical and tribological properties of PE-HD and not to other common issues occurring in recycling that can affect material properties, such as inorganic or polymer-based contamination. This was because source, type and quantity of contamination are highly unpredictable and vary from one recycling stream to another, making a fundamental or foundational study on this topic very challenging. Our study is subsequently scoped to the reprocessing aspect of recyclability.

Virgin granulates (1 × samples i.e., processed once from granulate

Table 2
High density polyethylene (PE-HD) virgin materials utilized in this study and ultra-high molecular weight polyethylene (PE-UHMW) used as a reference in tribology tests.

Name	Grade	Density (g/cm^3)	Colour	Intended application	Additives
HD-Pack	Borealis Borstar™ FB3450	0.945	White	Packaging films	Antioxidant
HD-Pipe	Borealis BorSafe™ HE3490 LS-H	0.960	Black	Pressure pipes	Pigments and UV stabilisers
HD-Cap	BorPure™ MB6561	0.955	White	Caps and closures	N/A
PE-UHMW reference	Ticona GUR 1050	0.932	White	Medical	N/A

into samples) were extruded using a single screw extruder (EX-18–26–1.5, Extron Engineering Oy, Finland) with a screw diameter of 18 mm, and a length to diameter ratio of 25:1, with a die of diameter 3 mm at 240 °C and 70 rpm screw speed, and a material feed rate of 0.75 kg/*h* ± 15%. The extruded material was subsequently ground into flakes using a mill (Fritsch Pulverisette 19, FRITSCH GmbH, Germany) to obtain the reprocessed samples. The reprocessing and grinding process was repeated ten times to obtain the reprocessed material (10 × samples). 10 × reprocessing of a material is an extreme case and represents the upper limit or an unlikely scenario based on currently available infrastructure.

2.3. *Crystallinity and mass flow rate of virgin and reprocessed PE-HD materials*

At least three strips ~100 μm in thickness were removed from the surface of each 1 × and 10 × scratch test sample using an automated rotary microtome (Microm HM 360, MICROM International GmbH, Germany). The crystallinity of these three strips was then measured for each sample using differential scanning calorimetry on a DSC Q2000 (TA Instruments, USA). Samples were heated to 260 °C before being cooled to 0 °C and then reheated to 260 °C at a rate of 10 K/min. Melting enthalpy (J/g) was calculated based on the melting peak of the 1st heating run using TA Universal Analysis software (v.4.5A) and a reference value for completely crystalline material (293 J/g) (Wunderlich, 1990).

The mass-flow rate (MFR) was measured for at least ten replicates of each sample according to ISO 1133–1 (International Organization for Standardization, 2022) at 190 °C under 5 kg load on the MeltFloW basic (Karg Industrietechnik, Germany).

2.4. *Compression moulding and preparation of the mechanical and tribological test specimens*

Virgin and reprocessed granulates were compression moulded (Collin P 200 P, Germany) at 180 °C and 50 bar with a cooling rate of 20 K/min to prepare tensile and impact, wear and scratch test specimens for all materials. At least ten dog-bone tensile (thickness 1.8–1.9 mm) and tensile impact test specimens (thickness 1.1–1.2 mm) were cut from each compression moulded sheet in accordance with ISO 527–2-A5 (International Organization for Standardization, 2012) and ISO 8256/1A (International Organization for Standardization, 2004), respectively. Tensile impact test specimens were notched with a Notch-Vis tool (Ceast, Germany). At least three circular discs of 30 mm diameter and 1.2 mm thickness were compression moulded for tribology tests of each sample and rectangular plates of dimensions 140 × 80 × 2 mm moulded for the scratch tests.

2.5. *Tensile (impact) testing of the virgin and reprocessed PE-HD samples*

A universal testing system comprising a Zwick 050 frame, 1 kN load cell and extensometer (Zwick Roell, Germany) was used to perform tensile tests on the prepared specimens at a constant velocity of 10 mm/min. The Young's modulus, yield strength and elongation at break were calculated using the ZwickRoell testXpert II software (v. 3.6) across five replicate tests. An Instron 9050 impact pendulum (Ceast, Germany) was used for tensile impact testing of the notched samples across at least ten replicates.

Table 3
Mass-flow rate under a 5 kg load (MFR, g/10 min) and crystallinity (%) of virgin (1 ×) and recycled (10 ×) PE-HD materials intended for packaging, pipes and caps/closures.

Material	MFR 5 kg (g/10 min)		Crystallinity of the test surface (%)	
	1 ×	10 ×	1 ×	10 ×
HD-Pack	0.94 ± 0.03	0.80 ± 0.01	55.0 ± 0.3	53.0 ± 0.4
HD-Pipe	0.22 ± 0.01	0.26 ± 0.01	58.2 ± 0.2	57.3 ± 0.4
HD-Cap	4.97 ± 0.21	3.96 ± 0.22	65.8 ± 0.7	63.4 ± 0.3

2.6. *Tribological testing of the virgin and reprocessed PE-HD samples*

Tribology tests were performed in unidirectional sliding mode with a

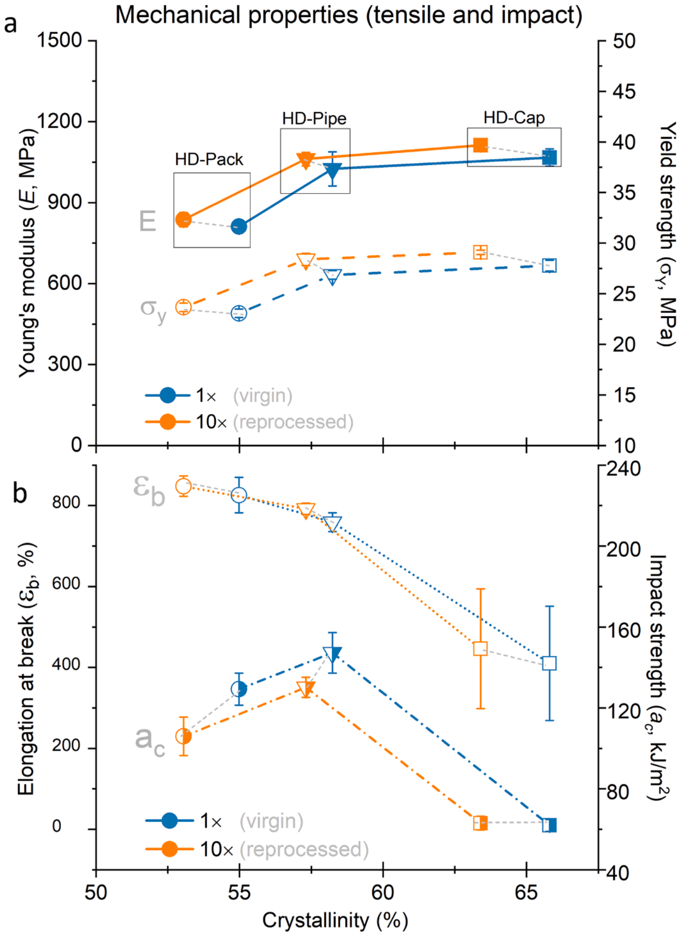

Fig. 2. (a) Young's modulus (*E*, MPa) and yield strength (σ_Y, MPa); and (b) elongation at break (ε_b,%) and impact strength (a_c, kJ/m^2) of virgin (1 × , blue) and 10 × reprocessed (orange) PE-HD samples intended for packaging, pipes and caps/closures.

ball-on-plate configuration according to ASTM G99 (ASTM International, 2017) using a Nanovea T50 tribometer (Nanovea, U.S.A). An AISI 440C steel ball 6 mm in diameter was used as the counter body under a 30 N load and at a speed of 35 mm/s for 30 min. Frictional force was recorded throughout the test and the associated coefficient of friction calculated.

Scratch tests were performed according to ISO 1518 (International Organization for Standardization, 2019) to investigate the underlying damage mechanisms of the polymers using an ERICHSEN 249 linear scratch tester (ERICHSEN GmbH & Co. KG, Germany) with a spherical steel scratch tip 1 mm in diameter at three constant loads (10, 20 and 30 N) approximately corresponding to 1, 2 and 3 kg loads, and two different speeds (22 and 200 mm/s).

Tribology and scratch test specimens were analysed using a VK-X1000 Laser Microscope (Keyence corporation, Japan). Image processing and analysis was completed using Keyence MultiFileAnalyzer software (v. 2.2.0.93). The cross-sectional area of wear tracks was averaged based on three measurements and multiplied by the average wear track circumference to obtain the total wear volume. This was performed for at least three test specimens per material.

Scratch width and depth were analysed for a 1 mm section centred on the scratch length for at least three replicate scratches for all six combinations of load and speed for each material.

3. Results and discussion

3.1. Processability and mechanical properties

PE-HD samples designed for packaging, pipe and cap/closure applications exhibited only a moderate change (i.e., 15–20%) in MFR following 10 × reprocessing and the recycled material could subsequently be processed using manufacturer-recommended methods (Table 3). The tensile and impact properties of 10 × reprocessed PE-HD were similar to values associated with virgin material (Fig. 2). The average Young's modulus E and elongation at break ε_b increased by 3–4% and 3–9%, respectively, for all 10 × reprocessed PE-HDs compared to virgin material and impact strength a_c decreased by 10–20% for 10 × reprocessed HD-Pack and HD-Pipe samples, while remaining unchanged for HD-Cap. Samples exhibited only modest changes in tensile properties for reprocessing cycles one to ten (Figure S1). The crystallinity of test surfaces reduced only slightly for 10 × reprocessed samples as compared to virgin materials. These results indicated that the recycled material had similar processability and mechanical properties to virgin material and could theoretically be used for similar applications (provided other requirements are not present e.g., food safety).

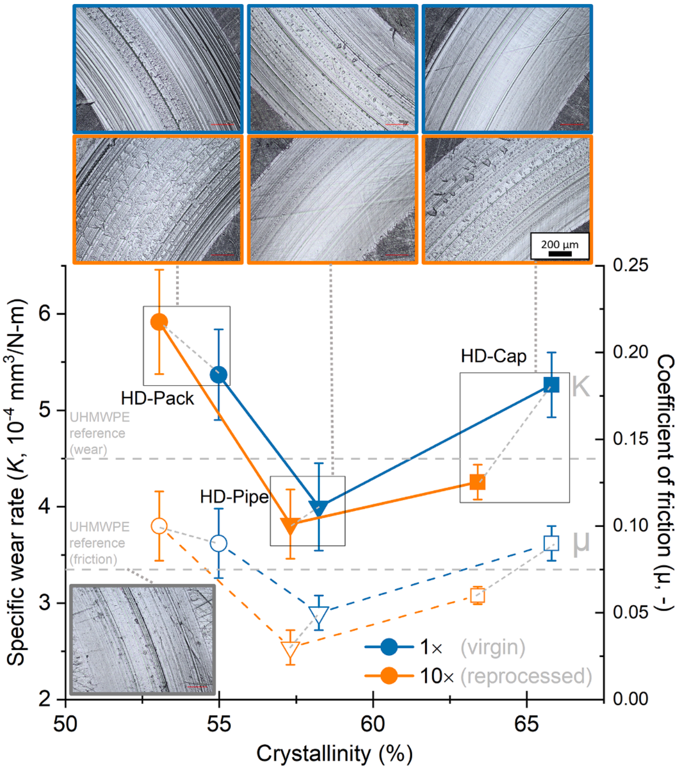

Fig. 3. Specific wear rate (K, mm^3/N•m), coefficient of friction (μ, -) and wear track morphology of virgin (1 × , blue) and 10 × reprocessed (orange) PE-HD samples intended for packaging, pipes and caps/closures as recorded during a 0.5 h ball-on-plate tribological test against a steel ball at 30 N load and 35 mm/s. Values and a micrograph for PE-UHMW are provided as a reference.

Reuse of recycled material in downcycled, "closed loop" or other equal value applications is already the subject of considerable research as documented in the literature (Barahona Osorio and Bruna Paez, 2020; Golkaram et al., 2022; Lonca et al., 2020; Lu and Johnson, 2011; Nosker and Lynch, 2013; Simon, 2019). Downcycling loops are not sustainable in the long term. By definition, they instantly result in decreased material value and utilise useful polymeric material for applications which could use alternatives with less interesting characteristics e.g., roads or composites could be filled with glass fines, rice hulls or low potential by-products (Scaffaro et al., 2021). Polymers also cannot be readily recovered once downcycled (Vogt et al., 2021). Recycling is a better option, however, since 90% of recycled material typically constitutes post-consumer waste (the vast majority of which is packaging) the applications of recycled material are very limited (Schyns and Shaver, 2021). Ideally the end product mirrors the original (closed-loop recycling to make packaging from packaging), a concept that has yet to be achieved in practice for PE-HD beyond milk containers (Gaduan et al., 2023), or a product with very similar material property requirements to the original product, for which the PE-HD was designed. Colour and odour problems in recycled PE-HD coupled with legal requirements associated with food packaging and reductions in mechanical properties during processing often make closed-loop recycling impossible (Golkaram et al., 2022).

Going a step further, when considered within the scope of a system rather than an individual component, new applications can be found for recycled PE-HD beyond those already exhausted in traditional part design practices. Some of these applications are sufficiently high in value that recycling can become upcycling. This increase in the value of recycled material may result in flow on effects for improved sorting and processing, the limiting factors for recycled material quality traditionally capped by the low economic value of recycled material. Improvement in the quality of recycled material would further expand the applications for which it can be used and result in further associated improvements in the economic value of the material and hence budget for sorting and processing improvements in an interconnected loop.

3.2. Potential new applications for recycled PE-HD: tribology

3.2.1. Friction and wear

The self-lubricating properties of polymers are one of the primary reasons for their use in tribological applications requiring low friction and wear. PE-UHMW has been extensively studied within the framework of medical applications, bearings, non-stick coatings for dump trucks, runners for production lines and medical implants (Ali et al., 2016; Chen et al., 2017; Kurtz, 2016) as it offers high wear and impact resistance, low friction and is inert to chemicals (Kurtz, 2016). PE-UHMW forms a thin transfer layer when rubbed against a steel counter body that reduces friction at interfaces and in many cases, entirely mitigates the need for lubrication. This transfer film results from localised bonding between the metal-polymer pair caused by adhesion between the two surfaces (Myshkin et al., 2005).

Studies on the tribology of virgin PE-HD suggest similar transfer

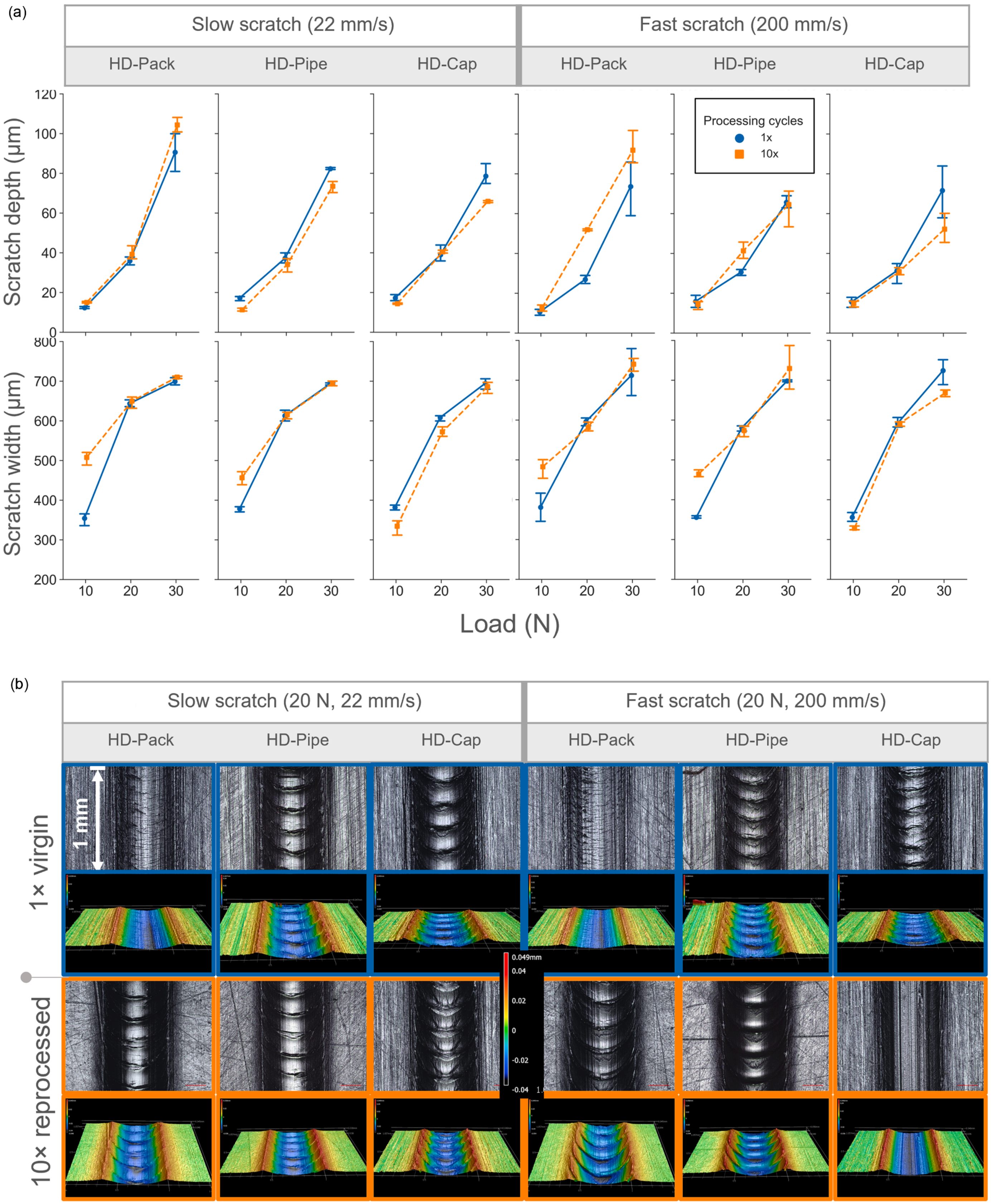

Fig. 4. (a) Scratch geometry characterised by width and depth (µm) and (b) morphology depicted using micrographs for virgin (1 × , blue) and 10 × reprocessed (orange) PE-HD samples intended for packaging, pipes and caps/closures scratched using 20 N load and a speed of 22 and 200 mm/s.

layer formation behaviour to PE-UHMW when rubbed against steel, albeit at slow speeds and moderate temperatures (Bahadur, 2000; Mergler et al., 2004), and it also exhibits low friction and wear (Bhushan, 2013). These properties in conjunction with the eco-preferred nature of PE-HD for a range of applications suggest possible new opportunities for the use of recycled PE-HD. The considerable comparative environmental benefit of recycled PE-HD compared to other polymers used in tribology, such as POM, PBT and PTFE—i.e., low energy requirements (27 MJ/kg compared to 103, 121 and 259 MJ/kg, respectively) and low CO_2 footprint (1.0 kg CO_2 eq./kg compared to 3.6, 4.4 and 11.7 kg CO_2 eq./kg, respectively) during manufacturing—means that the use of recycled PE-HD in even small masses or volumes as opposed to these other polymers used in tribology could be more environmentally significant than other larger mass or volume substitutions between polymers with smaller differences in environmental footprint (Jones et al., 2022). An additional advantage of PE-HD over PE-UHMW is the cost: PE-UHMW is manufactured by a sintering process and hence much more expensive than PE-HD. Most tribological studies relating to virgin PE-HD focus on a single PE-HD grade – usually low MFR grade (da Silva et al., 1999; Komoto et al., 1982; Molinari and Tuckart, 2016; Ponnuruthiyil Shaji et al., 2019; Xu et al., 2012). Even fewer studies have investigated the tribological properties of recycled PE-HD and only as a constituent in a composite (Aldousiri et al., 2013; Brostow et al., 2016).

10 × reprocessed PE-HD exhibited a similar wear mechanism and wear track geometry to virgin (1 ×) PE-HD samples, indicating that multiple reprocessing during recycling does not negatively affect PE-HD's tribological properties or its potential for adoption in tribological applications (Fig. 3). The material removal mechanism tended more towards abrasion for lower crystallinity and adhesion for higher crystallinity samples. HD-Pack, the least crystalline material, exhibited ploughing marks parallel to the wear track that suggest a combination of adhesive-abrasive wear. HD-Pipe and -Cap, which were more crystalline and have a lower molar mass (high MFR and high crystallinity), exhibited a wear mechanism comparable to that of PE-UHMW (Kanaga Karuppiah et al., 2008).

The coefficient of friction (μ) of reprocessed PE-HD was also no different than that of virgin PE-HD, with all materials exhibiting a $\mu < 0.1$. All three of the reprocessed PE-HDs, exhibited a wear rate and μ similar to that of PE-UHMW.

3.2.2. *Scratch resistance*

Understanding surface deformation behaviour during scratching provides an indication of the abrasion resistance of a material, as scratching can be considered equivalent to single-asperity abrasion (Briscoe, 1998). Both virgin (1 ×) and 10 × reprocessed PE-HD largely exhibited the same scratch width and depth, regardless of scratching speed (Fig. 4a). Scratch depth increased with increasing load but this effect was less pronounced in PE-HD with a higher degree of crystallinity. In short-chain polymers such as HD-Cap, an effective entanglement of the chains led to higher crystallinity—close to 65% of the scratch test surface was crystalline for both 1 × and 10 × —which in turn improved scratch resistance (Hadal and Misra, 2005) in both virgin and reprocessed samples. Scratch width increases were especially sensitive between 10 and 20 N at both speeds suggesting a threshold for the maximum tensile surface stress based on associated contact pressures.

Scratch morphology at 20 N load (Fig. 4b) varied between virgin (1 ×) and 10 × reprocessed samples. All samples exhibited clear evidence of visco-elastic material flow, visible as fish scale patterns with the exception of virgin (1 ×) HD-Pack. The structure of these patterns is caused by stick-slip i.e., breakage of localised bonds between the scratch tip and the polymer surface (Jiang et al., 2015). Plastic deformation, and its associated shoulder on the sides of the scratch, was greater for 10 × reprocessed material for all tested PE-HD grades. Both scratch damage modes are expected for ductile but weak polymers at the given contact pressure (Jiang et al., 2009). Scratch testing could be extended to investigate scratch visibility using various indenters in support of "design from recycling" practices where optical properties are important.

4. Conclusion

The processability (MFR variations of 15–20%), mechanical properties (E and ε_b variations <10% and a_c variations of 10–20%) and associated application-specific suitability of reprocessed PE-HD are similar to those associated with virgin PE-HD, although they do vary by grade. From a traditional component design perspective, this makes reprocessed PE-HD likely suitable for similar equal value applications to virgin PE-HD (as opposed to downcycling). Reprocessed PE-HD can, however, also be used in higher-value applications in an upcycling process through a simple switch in thinking: from an individual component exposed to external influences, to a component within a system acted upon by other known components within the system, resulting in a different set of design requirements. The case of reprocessed PE-HD in the field of tribology demonstrates this: Reprocessed PE-HD may not be suitable for many engineering applications, closed loop packaging or similar, but design requirements shift within a fixed (tribological) system from mechanical to tribological properties. Within the scope of the new requirements, PE-HD is comparable to PE-UHMW (similar wear mechanism and coefficient of friction < 0.1), which is commonly used in products that have a value consistent with upcycling, such as bearings. Repeated reprocessing of PE-HD also doesn't affect its tribological properties or potential for adoption in tribological applications, i.e., there is no loss of properties, with both virgin and reprocessed PE-HD exhibiting a similar wear mechanism, wear track geometry and coefficient of friction. Although tribology is a system property that depends entirely on the testing conditions and subsequently would require additional application-specific tests to establish possible new applications in tribology, recycled PE-HD could potentially replace other preferred polymers in some tribological applications. This constitutes expansion of recycled material to new applications. The importance and necessity of this expansion cannot be overstated: There are currently insufficient applications and markets for recycled materials to meet looming EU targets and legislation. The adoption of recycled material in previously unconsidered applications will increasingly become a priority for industry as they struggle to meet their legal obligations. More broadly, as environmental sustainability and resource conservation are prioritised, recycling and use of recycled materials are going to need to grow considerably and get smarter. Many issues with the quality of recycled materials are at least partially attributable to the necessity of keeping sorting and reprocessing costs down due to the restricted and low-value applications for these materials. The use of recycled material in higher-value applications (upcycling) could increase its value and provide budget for improvements in quality during the recycling process.

CRediT authorship contribution statement

Harsha Raghuram: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing – original draft. **Julia Roitner:** Resources, Methodology, Investigation. **Mitchell P. Jones:** Conceptualization, Writing – review & editing. **Vasiliki-Maria Archodoulaki:** Conceptualization, Supervision, Methodology, Funding acquisition, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Acknowledgements

We thank Borealis AG for providing the PE-HD materials used in this study and the TU Wien Bibliothek for financial support through its Open Access Funding Programme.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.106925.

References

Aldousiri, B., Alajmi, M., Shalwan, A., 2013. Mechanical properties of palm fibre reinforced recycled HDPE. Adv. Mater. Sci. Eng. 2013, 1–7. https://doi.org/10.1155/2013/508179.

Ali, M., Al-Hajjar, M., Jennings, L.M., 2016. Tribology of UHMWPE in the hip. UHMWPE Biomaterials Handbook. Elsevier, pp. 579–598. https://doi.org/10.1016/B978-0-323-35401-1.00031-4.

ASTM International, 2017. ASTM G99-17 - standard test method for wear testing with a pin-on-disk apparatus. https://doi.org/10.1520/G0099-17.

Bahadur, S., 2000. The development of transfer layers and their role in polymer tribology. Wear 245, 92–99. https://doi.org/10.1016/S0043-1648(00)00469-5.

Barahona Osorio, G.I., Bruna Paez, S.M., 2020. Method for recycling high-density polyethylene (HDPE) material by thermofusion and recycled HDPE products. European patent 3527345A4.

Benoit, N., González-Núñez, R., Rodrigue, D., 2017. High density polyethylene degradation followed by closed-loop recycling. Prog. Rubber, Plast. Recycl. Technol. 33, 17–38. https://doi.org/10.1177/147776061703300102.

Bhushan, B., 2013. Principles and Applications of Tribology. John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex. https://doi.org/10.1002/9781118403020. PO19 8SQ, UK.

Briscoe, B., 1998. Isolated contact stress deformations of polymers: the basis for interpreting polymer tribology. Tribol. Int. 31, 121–126. https://doi.org/10.1016/S0301-679X(98)00014-0.

Brostow, W., Datashvili, T., Jiang, P., Miller, H., 2016. Recycled HDPE reinforced with sol–gel silica modified wood sawdust. Eur. Polym. J. 76, 28–39. https://doi.org/10.1016/j.eurpolymj.2016.01.015.

Chen, S., Li, J., Wei, L., Jin, Y., Shang, H., Hua, M., Duan, H., 2017. Tribological properties of polyimide-modified UHMWPE for bushing materials of seawater lubricated sliding bearings. Tribol. Int. 115, 470–476. https://doi.org/10.1016/j.triboint.2017.06.011.

Chrysafi, I., Asimakidou, T., Michailidou, G., Xanthopoulou, E., Tziamtzi, C.K., Zamboulis, A., Bikiaris, D.N., 2022. Characterization of the thermal, structural, and mechanical properties of recycled HDPE. Macromol. Symp. 405, 10–12. https://doi.org/10.1002/masy.202100224.

da Silva, C.H., Tanaka, D.K., Sinatora, A., 1999. The effect of load and relative humidity on friction coefficient between high density polyethylene on galvanized steel—preliminary results. Wear 225–229, 339–342. https://doi.org/10.1016/S0043-1648(98)00365-2.

Durane, L., Mlinaric, J.-.M., 2017. Recycling of high-density polyethylene from domestic polymer waste. European patent 2697025B1.

Gaduan, A.N., Li, J., Hill, G., Wallis, C., Burgstaller, C., Lee, K.-.Y., 2023. Simulating the recycling of milk bottles in the UK: influence of blending virgin and repeatedly melt-extruded high-density polyethylene. Resour. Conserv. Recycl. 189, 106734 https://doi.org/10.1016/j.resconrec.2022.106734.

Golkaram, M., Mehta, R., Taveau, M., Schwarz, A., Gankema, H., Urbanus, J.H., De Simon, L., Cakir-Benthem, S., van Harmelen, T., 2022. Quality model for recycled plastics (QMRP): an indicator for holistic and consistent quality assessment of recycled plastics using product functionality and material properties. J. Clean. Prod. 362, 132311 https://doi.org/10.1016/j.jclepro.2022.132311.

Hadal, R.S., Misra, R.D.K., 2005. Scratch deformation behavior of thermoplastic materials with significant differences in ductility. Mater. Sci. Eng. A 398, 252–261. https://doi.org/10.1016/j.msea.2005.03.028.

International Organization for Standardization, 2022. ISO 1133-1:2022 - plastics — determination of the melt mass-flow rate (MFR) and melt volume-flow rate (MVR) of thermoplastics — part 1: standard method.

International Organization for Standardization, 2019. ISO 1518-1:2019 - general test methods for paints and varnishes.

International Organization for Standardization, 2012. ISO 527-2:2012 - Plastics — determination of tensile properties — part 2: test conditions for moulding and extrusion plastics.

International Organization for Standardization, 2004. ISO 8256:2004 - Plastics — determination of tensile-impact strength.

Jiang, H., Browning, R., Sue, H.J., 2009. Understanding of scratch-induced damage mechanisms in polymers. Polymer (Guildf) 50, 4056–4065. https://doi.org/10.1016/j.polymer.2009.06.061.

Jiang, H., Cheng, Q., Jiang, C., Zhang, J., Yonghua, L., 2015. Effect of stick-slip on the scratch performance of polypropylene. Tribol. Int. 91, 1–5. https://doi.org/10.1016/j.triboint.2015.06.024.

Jones, M.P., Archodoulaki, V.-.M., Köck, B.-.M., 2022. The power of good decisions: promoting eco-informed design attitudes in plastic selection and use. Resour. Conserv. Recycl. 182, 106324 https://doi.org/10.1016/j.resconrec.2022.106324.

Kanaga Karuppiah, K.S., Bruck, A.L., Sundararajan, S., Wang, J., Lin, Z., Xu, Z.H., Li, X., 2008. Friction and wear behavior of ultra-high molecular weight polyethylene as a function of polymer crystallinity. Acta Biomater. 4, 1401–1410. https://doi.org/10.1016/j.actbio.2008.02.022.

Karaagac, E., Jones, M.P., Koch, T., Archodoulaki, V.-.M., 2021. Polypropylene contamination in post-consumer polyolefin waste: characterisation, consequences and compatibilisation. Polymers (Basel) 13, 2618. https://doi.org/10.3390/polym13162618.

Komoto, T., Tanaka, K., Hironaka, S., Matsumoto, T., Takano, N., 1982. Morphological study of the wear of crystalline polymers I: high density polyethylene. Wear 75, 173–182. https://doi.org/10.1016/0043-1648(82)90146-6.

Kurtz, S.M., 2016. A primer on UHMWPE. UHMWPE Biomaterials Handbook. Elsevier, pp. 1–6. https://doi.org/10.1016/B978-0-323-35401-1.00001-6.

Lonca, G., Lesage, P., Majeau-Bettez, G., Bernard, S., Margni, M., 2020. Assessing scaling effects of circular economy strategies: a case study on plastic bottle closed-loop recycling in the USA PET market. Resour. Conserv. Recycl. 162, 105013 https://doi.org/10.1016/j.resconrec.2020.105013.

Lu, N., Johnson, R.R., 2011. Hemp fiber reinforced composite with recycled high density polyethylene and production thereof. US patent 20120046394A1.

Manica, U.-.K., 2013. Method for the treatment of recycled HDPE. European patent 2770016A1.

Mendes, A.A., Cunha, A.M., Bernardo, C.A., 2011. Study of the degradation mechanisms of polyethylene during reprocessing. Polym. Degrad. Stab. 96, 1125–1133. https://doi.org/10.1016/j.polymdegradstab.2011.02.015.

Mergler, Y.J., Schaake, R.P., Huis in't Veld, A.J., 2004. Material transfer of POM in sliding contact. Wear 256, 294–301. https://doi.org/10.1016/S0043-1648(03)00410-1.

Molinari, E.C., Tuckart, M.D.F.W.R., 2016. The effect of crosslinks on the sliding wear of high-density polyethylene. Tribol. Lett. 64, 1–12. https://doi.org/10.1007/s11249-016-0763-y.

Myshkin, N.K., Petrokovets, M.I., Kovalev, A.V., 2005. Tribology of polymers: adhesion, friction, wear, and mass-transfer. Tribol. Int. 38, 910–921. https://doi.org/10.1016/J.TRIBOINT.2005.07.016.

Nosker, T., Lynch, J., 2013. Composite articles compression molded from recycled plastic. Patent WO2014089062A1.

Oblak, P., Gonzalez-Gutierrez, J., Zupančič, B., Aulova, A., Emri, I., 2015. Processability and mechanical properties of extensively recycled high density polyethylene. Polym. Degrad. Stab. 114, 133–145. https://doi.org/10.1016/j.polymdegradstab.2015.01.012.

Plastics Europe, 2022. The circular economy for plastics - a European overview.

Ponnuruthiyil Shaji, A., Shaik, M.A., Golla, B.R., 2019. Mechanical, wear, and dielectric behavior of TiO 2 reinforced high-density polyethylene composites. J. Appl. Polym. Sci. 136, 47610. https://doi.org/10.1002/app.47610.

Ragaert, K., Huysveld, S., Vyncke, G., Hubo, S., Veelaert, L., Dewulf, J., Du Bois, E., 2020. Design from recycling: a complex mixed plastic waste case study. Resour. Conserv. Recycl. 155, 104646 https://doi.org/10.1016/j.resconrec.2019.104646.

Scaffaro, R., Di Bartolo, A., Dintcheva, N.T., 2021. Matrix and filler recycling of carbon and glass fiber-reinforced polymer composites: a review. Polymers (Basel) 13, 3817. https://doi.org/10.3390/polym13213817.

Schweighuber, A., Felgel-Farnholz, A., Bögl, T., Fischer, J., Buchberger, W., 2021. Investigations on the influence of multiple extrusion on the degradation of polyolefins. Polym. Degrad. Stab. 192, 109689 https://doi.org/10.1016/j.polymdegradstab.2021.109689.

Schyns, Z.O.G., Shaver, M.P., 2021. Mechanical recycling of packaging plastics: a review. Macromol. Rapid Commun. 42, 1–27. https://doi.org/10.1002/marc.202000415.

Shaneour, D., 1995. Playground structural member using recycled plastic. US patent 5557900A.

Simon, B., 2019. What are the most significant aspects of supporting the circular economy in the plastic industry? Resour. Conserv. Recycl. 141, 299–300. https://doi.org/10.1016/j.resconrec.2018.10.044.

Stachowiak, G.W., Batchelor, A.W., 2005. Engineering tribology, Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-397047-3.00018-7.

Vogt, B.D., Stokes, K.K., Kumar, S.K., 2021. Why is recycling of postconsumer plastics so challenging? ACS Appl. Polym. Mater. 3, 4325–4346. https://doi.org/10.1021/acsapm.1c00648.

Wunderlich, B., 1990. Calorimetry. Thermal Analysis. Elsevier, pp. 219–310. https://doi.org/10.1016/B978-0-12-765605-2.50009-1.

Xu, S., Akchurin, A., Liu, T., Wood, W., Tangpong, X.W., Akhatov, I.S., Zhong, W.-.H., 2012. Wear and friction of carbon nanofiber-reinforced HDPE composites. J. Tribol. 134, 041602 https://doi.org/10.1115/1.4007016.