

# **Investigating Thermal and Processing Effects on High Density Polyethylene (HDPE) Properties**

William Cusato, Matti Kruger, Delaney McLynch, Zakora Moore, Adrian Roop

ME114 - Polymer Materials and Processing

12/08/2025

## **Introduction and Purpose**

Polymers occupy a uniquely versatile space in modern engineering because their mechanical behavior can vary dramatically with temperature and processing history. Unlike metals, which typically maintain predictable strength across moderate temperature ranges, polymers may soften, embrittle, toughen, or undergo transitions that fundamentally change how they deform and fail. These temperature-dependent responses arise from their molecular architecture—chain mobility, crystallinity, molecular weight, and intermolecular bonding—and are further shaped by manufacturing processes such as extrusion, injection molding, and additive manufacturing. As a result, engineers must understand not only the inherent material properties of a given polymer but also how the thermal environment and processing route can modify these properties.

In this lab, tensile testing is used to experimentally explore how HDPE changes in mechanical performance across multiple temperatures. By manufacturing standardized dogbone specimens using extrusion and injection molding, a controlled framework for isolating the influence of both thermal conditions and processing methods can be achieved. The Instron testing system, paired with a temperature chamber, allows for direct comparison of stiffness, yield behavior, ductility, and failure modes at temperatures that bracket each polymer's glass transition regime. This combination of material diversity and processing variety mirrors real-world engineering design, where polymer components must reliably function across environments ranging from freezer storage to high-heat consumer electronics.

The purpose of this lab is to investigate how the tensile properties of various polymers depend on both temperature and manufacturing method, and to relate these findings to practical material selection. By testing materials at several temperatures—including conditions near or above their glass transition temperature—it can be identified how strength, stiffness, and ductility evolve as polymer chain mobility increases or decreases. Understanding these trends is essential for predicting when a polymer will be tough and ductile versus brittle and failure-prone, and for determining safe operating temperature ranges in both industrial and household applications.

Equally important is evaluating how extrusion, injection molding, and 3D printing influence microstructure and therefore mechanical performance. Because factors such as cooling rate, molecular orientation, and crystallinity differ across processes, identical polymers may exhibit noticeably different strengths or failure mechanisms depending on how they were manufactured. By combining thermal and processing effects, skills regarding material selection and fabrication routes that ensure reliability in real-world products are developed.

## **Material Description**

### **History and Purpose of HDPE**

High-Density Polyethylene (HDPE) is one of the most widely utilized and recognizable thermoplastic materials in modern manufacturing, identifiable by the resin code #2. Its introduction revolutionized the plastics industry by providing a material that combined lightness with superior strength and chemical resistance. The journey to HDPE began with the discovery of general polyethylene (PE) in the 1930s by

British chemists Eric Fawcett and Reginald Gibson, a process that required immense pressure and high temperatures, resulting in a low-density, highly branched polymer (LDPE) initially used for radar cable insulation during World War II [1]. The true breakthrough, however, was the development of a low-pressure method that allowed for the creation of a linear, high-density variant.

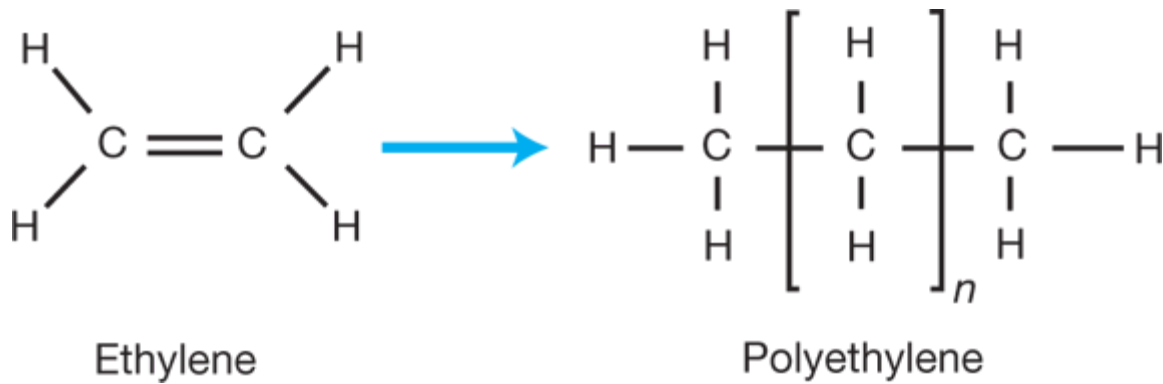
The pivotal moment for HDPE occurred in the early 1950s with two independent, groundbreaking discoveries. At Phillips Petroleum Company in 1951, chemists J. Paul Hogan and Robert L. Banks utilized a chromium oxide catalyst to successfully polymerize ethylene at remarkably lower pressures, creating the much stiffer, more crystalline plastic they branded as Marlex [2]. Concurrently, in Germany, Karl Ziegler and Erhard Holzkamp developed their own catalytic process in 1953, earning Ziegler the 1963 Nobel Prize in Chemistry. The success of these low-pressure methods was rooted in the resulting molecular structure: unlike the branched chains of LDPE, HDPE possesses an organized, linear structure that allows the molecules to pack tightly, increasing its density (typically 0.941 to 0.965 g/cm<sup>3</sup>) and resulting in its characteristic rigidity and high tensile strength [1].

Despite its initial commercial introduction by Phillips in 1954, HDPE initially struggled to find a market, leading to stockpiling. The polymer's commercial turning point arrived unexpectedly in 1956 with the introduction of the Hula Hoop, which was manufactured using the newly available plastic [1, 3]. This fad rapidly consumed Phillips' inventory and cemented HDPE's presence in the consumer market. From there, its true, enduring purpose—to create robust, long-lasting products—was realized.

The primary purpose of HDPE is to provide a material with a high strength-to-density ratio, making it an ideal choice for durable applications where conventional materials like metal or glass are impractical or cost-prohibitive. This is achieved through its defining properties, which include excellent chemical resistance to acids, bases, and solvents, low moisture absorption, and a high melting point compared to LDPE (120 °C to 130 °C) [4]. Today, its applications are vast and essential to modern infrastructure and consumer goods. HDPE is the dominant material in rigid packaging, such as milk jugs and detergent bottles (accounting for one-third of worldwide production), and is widely used for corrosion-resistant piping systems in municipal water and gas distribution [1, 2]. Furthermore, its durability and UV resistance make it highly valuable in outdoor products, including playground equipment, plastic lumber, and geomembranes used in environmental containment like landfill liners [4]. As a commonly recycled plastic (code #2), HDPE also supports the transition to a circular economy, demonstrating its lasting impact on both industry and sustainability.

## **Composition of Material**

High-Density Polyethylene is a semi-crystalline thermoplastic polymer derived from the monomer ethylene. Its chemical structure is simple: a long, straight chain of carbon atoms with two hydrogen atoms bonded to each carbon, resulting in the repeat unit [5].



*Figure 1: Chemical Structure of Polyethylene (PE)*

HDPE's higher density and superior strength are due to its predominantly linear molecular architecture with minimal side-branching. This linearity permits the polymer chains to pack tightly together, resulting in a high degree of crystallinity, typically ranging from 70% to 90% [6].

To appreciate HDPE's properties, it is essential to compare it with other polyethylene variants, as the degree and type of branching fundamentally define the material's characteristics:

*Table 1: Comparison of Polyethylene (PE) Variations [6, 7]*

Polymer	Molecular Structure	Branching	Crystallinity	Density (g/cm <sup>3</sup> )	T <sub>g</sub> (°C)	Key Property
HDPE	More Linear Chains	Minimal	High (70% – 90%)	0.950 – 0.960	-120	High Stiffness
LDPE	Longer Branches	Extensive	Low (40% – 60%)	0.920 – 0.930	-120	Flexibility
LLDPE	Shorter Branches	Short Branches	Low (30% – 45%)	0.922 – 0.926	-125	Puncture Resistance

Some key characteristics of HDPE is its low glass transition temperature [7]. This means that at room temperature, the amorphous regions of the polymer are in the tough, rubbery state, contributing to its excellent flexibility and impact resistance even at low temperatures. Additionally, in HDPE, the crystalline regions melt over a range typically between 120 C and 140 C. This melting point allows it to be used in applications requiring moderate heat resistance as well as relatively easy melt processability in techniques such as extrusion and injection molding. These characteristics are directly related to the tensile testing performed in this lab. Because HDPE's crystallinity, chain alignment, and amorphous mobility vary with both temperature and processing method, changes in modulus, yield strength, and ductility were expected across the tested temperature range. Additionally, the differences between extrusion and injection molding observed in the experiment arise from the same structural factors described here—namely cooling rate, molecular orientation, and the development of crystalline regions.

## Common Applications of Material:

HDPE's high strength-to-density ratio, outstanding chemical resistance, and ease of processing make it one of the most widely used plastics globally. Its common applications are driven by its durability and ability to resist environmental factors [8].

- *Rigid Packaging and Containers:* HDPE is favored for blow molding applications such as milk jugs, detergent and bleach bottles, and large chemical containers. Its chemical resistance ensures compatibility with aggressive fluids, while its stiffness provides structural integrity for stacking and transport [8, 9]
- *Piping Systems and Infrastructure:* The material's corrosion resistance and long-term durability make it the material of choice for water supply lines, gas distribution pipes, and sewage systems. It is also used in the form of geomembranes for lining landfills and water containment ponds [8, 9]
- *Consumer and Industrial Products:* Applications that benefit from its rigidity and weather resistance include plastic lumber, children's toys, outdoor playground equipment, and large storage bins [8].

## Recyclability

HDPE is identified by the resin identification code "2" and is considered one of the most readily recyclable and economically viable polymers [10].

The recycling process typically involves shredding, washing, melting, and reforming the material into new pellets or products. The success of recycling HDPE is largely attributed to its relatively simple, non-polar structure and its market demand in applications like composite lumber and drainage pipes.

Another critical factor determining HDPE's mechanical properties is its molecular weight. The length of the polymer chains affects viscosity, melt temperature, flexibility, and yield strength. Higher MW generally correlates with improved toughness, chemical resistance, and environmental stress crack resistance, but can make the polymer more difficult to process [5]. The specific grade of HDPE used often determines its final properties, such as Melt Flow Index (MFI), which is critical for choosing the appropriate manufacturing method.

## Injection Molding and Extrusion Processes

Injection molding and extrusion are both common, cost-effective ways to make parts from high-density polyethylene (HDPE), but they suit very different part types and expose the resin to different thermal and mechanical histories — which changes how you design, choose a grade, and control processing. Injection molding is a batch, cavity-based process that forces molten HDPE into a closed tool to form discrete, often complex 3-D parts with close tolerances. It's ideal when you need detailed geometry, ribs, bosses, or snap-fits, and when surface finish and dimensional repeatability matter. However, HDPE's semi-crystalline nature makes it prone to shrinkage, warpage and residual stress if cooling is uneven or packing/cycle settings are off, so careful mold design, gate placement, and process control are critical [11, 12].

Extrusion, by contrast, is a continuous process: pellets are melted and forced through a die to produce constant-cross-section products (pipe, tubing, sheet, film, profiles). It's the natural choice when you need long, uniform lengths or thin films and when steady-state throughput and economy are priorities. Extrusion typically places different demands on HDPE grades — melt strength, melt index (flow), and resistance to prolonged thermal exposure are more important than the rapid-cycle rheology prized in injection molding. Many commercial HDPE grades are formulated and databased for both extrusion and injection, with manufacturers listing recommended grades and their properties so designers can match melt flow and stiffness to the process and part [13, 14].

Practically, production economics and part function drive the choice. Injection molding has higher tooling cost and longer upfront lead times but produces complex parts with low post-processing; per-part cost falls quickly at high volumes. Extrusion tooling is usually cheaper and faster to iterate, and per-meter costs are low for long runs, but you're limited to profiles and often need downstream cutting, thermoforming or welding for finished parts. From a materials-engineering standpoint, expect different defect modes: injection parts suffer from localized warpage and dimensional variation if cooling is nonuniform, while extruded products must manage die swell, melt fracture, and long-time thermal degradation or orientation effects. For practical process comparison and decision guidance see technical articles comparing extrusion vs. injection and manufacturer HDPE product guides [13, 15].

## **Lab Procedures**

### **Creating Extruded Samples**

The fabrication of extruded HDPE dogbone specimens was performed using a ShopBot CNC machine with proper safety protocols and machine preparation. All operators completed required Bray staff training before machine use. The machine was powered on via the main switch and key control, and the interior was thoroughly cleaned of debris using the adjacent vacuum system.

A 1/8-inch uppercut square bit was installed and verified against the tool storage section. The ShopBot software was launched and switched to "full mode" to access complete machine functions. Before material loading, the spindle warmup routine was executed from the "cuts" menu. During this warmup period, the dogbone pattern file (.log format) was downloaded from Canvas and the material thickness parameter was precisely adjusted using caliper measurements of the actual HDPE stock. This thickness adjustment was critical to prevent cutting into the wooden spoilboard beneath the material.

After warmup completion, the HDPE sheet was positioned on the cutting bed and secured with clamps on all sides to prevent movement during machining. The cutting bit was manually positioned to the desired starting location using the control panel interface. The zeroing procedure utilized an inside corner orientation routine with a specialized metal platform and clamp attached to the bit. When prompted, the bit size (0.125 inches) was entered, and the orientation routine was initiated. Upon completion, the reference hardware was removed and all control panels were closed to prevent software crashes.

The cutting operation was initiated and continuously monitored to ensure the bit did not penetrate the spoilboard. Upon completion, the dogbone sample was freed by manually cutting three intentional

connecting tabs designed to maintain stability during machining. Additional samples were produced by repositioning the bit to unused areas of the HDPE sheet and repeating the cutting sequence. After all samples were fabricated, proper cleanup protocols were followed to maintain a safe operating environment free of particulates and debris. All materials and tooling were returned to their designated storage locations, and the machine was properly shut down according to standard procedures [16].

The machined dogbone specimens conformed to ASTM D638 Type 1 tensile bar geometry specifications [17]. Key dimensions included a gauge length of 2.00 inches, overall length of 6.5 inches, narrow section width of 0.5 inches, grip section width of 0.75 inches, gauge section length of 2.25 inches, total specimen length between grips of 4.5 inches, and fillet radius of 3.00 inches. These specific dimensions ensure uniform stress distribution during testing and minimize stress concentrations that could lead to premature failure outside the gauge section [17].

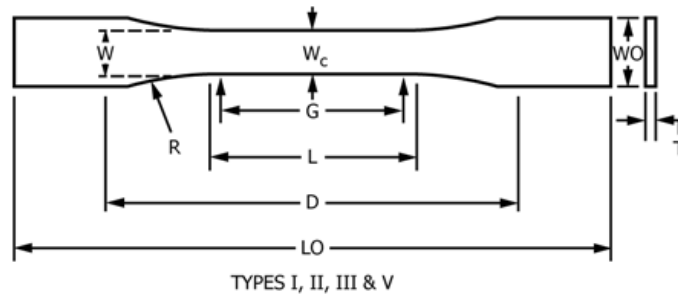


Figure 2: Schematic of Type 1 Dogbone [17]

Table 2: Dimensions of Type 1 Dogbone [17]

W	L	Wo	Lo	G	D	R
0.5 in	2.25 in	0.75 in	6.5 in	2.00 in	4.5 in	3.00 in

### Creating Injection Molded Samples

Injection molded HDPE specimens were fabricated to compare the mechanical properties resulting from different processing methods. However, the injection molding process encountered significant challenges due to improper pre-treatment of the HDPE pellet feedstock [18]. In conversation with those who created the injection molded samples, it was expressed that the pellets may have absorbed water while in storage [18]. When the moisture-laden pellets entered the heated injection molding barrel, the absorbed water rapidly vaporized, creating steam bubbles within the polymer melt. These vapor pockets were subsequently injected into the mold cavity along with the polymer, resulting in incomplete cavity filling and inadequate packing pressure throughout the part. While HDPE does not readily absorb large amounts of moisture, even miniscule imperfections in material handling during manufacturing processes can lead to disastrous outcomes. The presence of voids and the insufficient packing pressure manifested as visible defects in the finished specimens, most notably a concave depression or "caving" along the centerline of

the dogbone gauge section [18]. This surface irregularity indicated that the mold cavity was not properly filled and that internal voids likely existed within the specimen cross-section.

The injection molded specimens also deviated from the standard ASTM D638 Type 1 geometry used for the extruded samples [17]. Most significantly, the gauge section width was reduced to 0.25 inches rather than the 0.5-inch width specified in the standard and used for extruded specimens. This dimensional difference, combined with the processing defects, complicated direct comparison between the two sample sets. The reduced cross-sectional area and the presence of internal voids due to improper packing resulted in diminished load-bearing capacity and compromised mechanical properties. Consequently, the injection molded specimens exhibited lower strength characteristics than would be expected from properly processed HDPE, making it difficult to isolate the true effects of the injection molding process from the artifacts introduced by inadequate material preparation and processing control.

## **Tensile Testing**

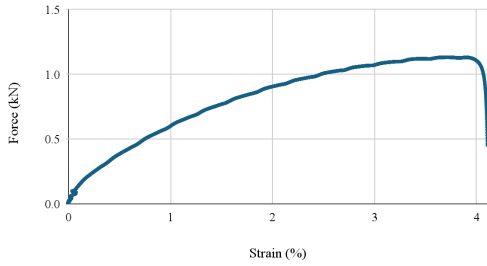
Tensile testing of the dogbone samples was conducted using an Instron 5800R Tensile and Compression Test System in accordance with ASTM D638, the standard test method for tensile properties of plastics [17]. ASTM D3039 specifies multiple test speeds depending on the desired strain rate and the material being tested. For this experiment, a strain rate of 2 mm/min was selected, which corresponds to Test Speed A as defined in the standard and is appropriate for determining general tensile properties of rigid and semi-rigid plastics [19]. Each dogbone sample was securely mounted in the pneumatic grips of the Instron machine, with care taken to ensure proper alignment to prevent induced bending moments during testing. To obtain precise strain measurements during the initial elastic and yield regions, a clip-on extensometer was attached directly to the gauge section of the specimen. This extensometer provided high-accuracy strain data that is superior to crosshead displacement measurements, as it eliminates compliance effects from the grips and load frame [20]. However, to protect the extensometer from damage during the post-yield deformation and potential fracture of the specimen, it was removed once the total deformation reached 4 mm. Beyond this point, strain measurements were calculated using the high-range extensometer integrated into the Instron chassis, which tracks crosshead displacement to determine elongation throughout the remainder of the test until specimen failure [21].

To comprehensively characterize the temperature-dependent mechanical behavior of HDPE, tensile tests were performed at five distinct temperatures:  $-100^{\circ}\text{C}$ ,  $-80^{\circ}\text{C}$ ,  $-50^{\circ}\text{C}$ ,  $20^{\circ}\text{C}$  (room temperature), and  $125^{\circ}\text{C}$ . These tests were conducted using the Instron's environmental chamber, which is equipped with both heating elements and a cryogenic gas cooling system, allowing for precise temperature control across a wide range [22]. This temperature range was specifically selected to capture the complete mechanical response of HDPE across all relevant thermal regions. The sub-zero temperatures allowed observation of HDPE in a more brittle, higher modulus state, where the polymer chains have lower mobility. The room temperature test ( $20^{\circ}\text{C}$ ) captured HDPE in its typical semi-crystalline state above the glass transition temperature, where it exhibits the characteristic toughness and ductility that make it useful for engineering applications [23]. The elevated temperature test at  $125^{\circ}\text{C}$ , which approaches the melting temperature range of HDPE, allowed observation of the material as crystalline regions begin to soften and melt, resulting in dramatic reductions in strength and stiffness [23, 24]. This comprehensive temperature sweep enabled a complete understanding of how HDPE's mechanical properties transition from glassy to rubbery to viscous behavior across its full operational temperature spectrum.

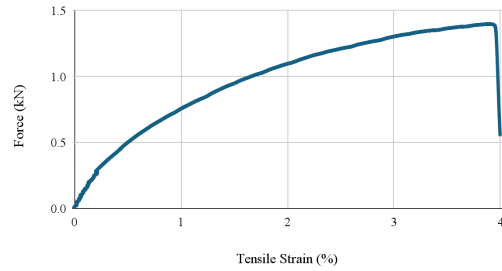
# Analysis of Results

## Instron Results

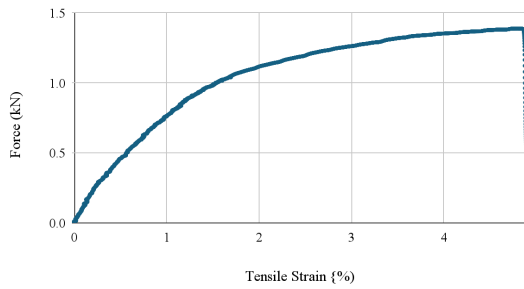
Force vs. Tensile Strain [-100 °C]



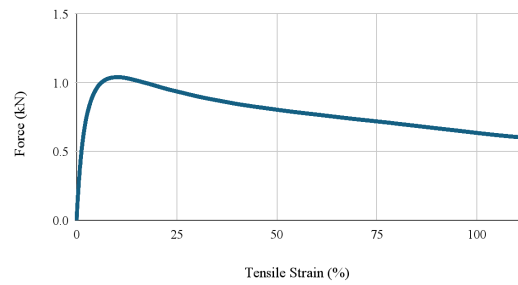
Force vs. Tensile Strain [-80 °C]



Force vs. Tensile Strain [-50 °C]



Force vs. Tensile Strain [20 °C]



Force vs. Tensile Strain [125 °C]

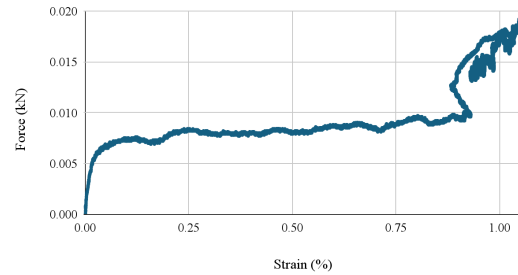
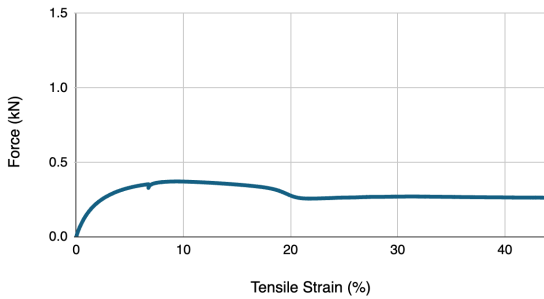


Figure 3: Force (kN) vs. Tensile Strain (%) of Extruded HDPE at Varying Temperature

Force vs. Tensile Strain [20 °C]



Force vs. Tensile Strain [20 °C]

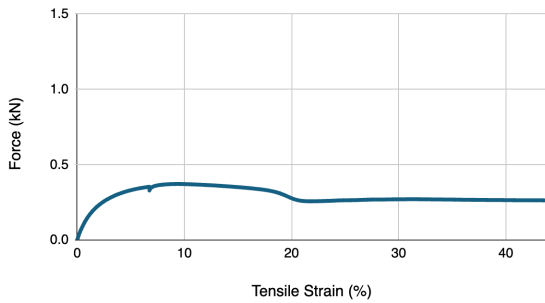


Figure 4: Force (kN) vs. Tensile Strain (%) of Injection Molded HDPE at Varying Temperature

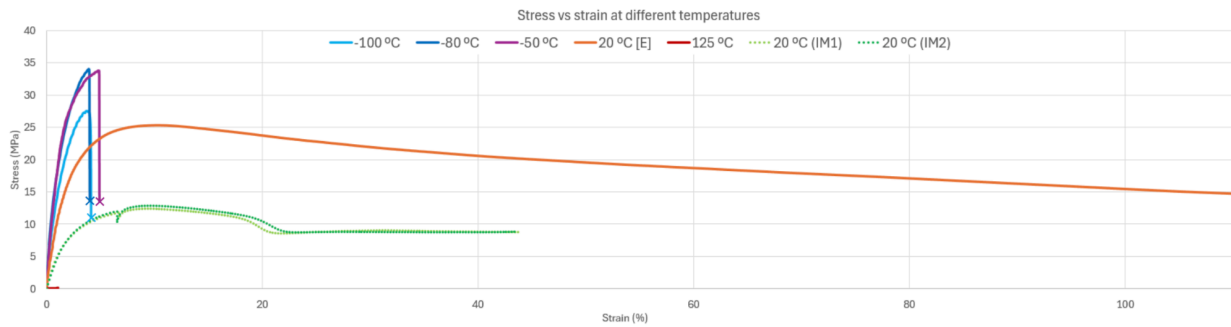


Figure 5: Superimposed Plot of Tensile Stress (MPa) vs. Strain (%) at Varying Temperatures

### Property Derivation

The Young's Modulus was calculated by finding the slope of the linear-elastic region for all tests. The values are summarized in the table below. It is important to note that the data obtained from last year's experiments was incorrect since the wrong cross-sectional area was input in the Instron, which severely impacted the reported stress values. This mistake was identified thanks to explicit ASTM standards, which are very detailed for the dimensions of the dogbone [17].

Table 3: Young's Modulus for all available data

Temperature (°C)	-100	-80	-50	20	125
E (GPa) [Extruded Samples]	2.20	3.42	2.60	1.21	0.27
E (GPa) [Injection Molded Samples]	N/A	N/A	N/A	0.80	N/A

Young's Modulus vs. Temperature

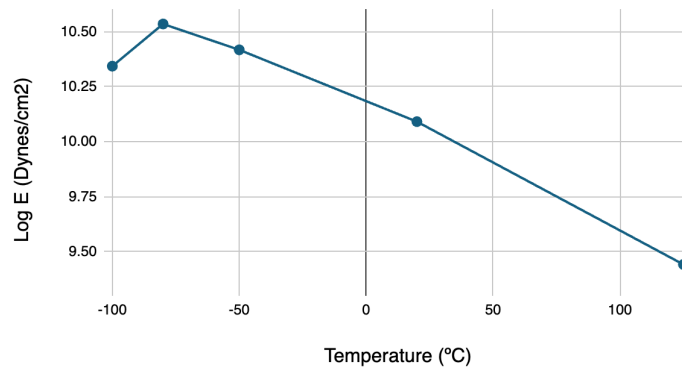


Figure 6: Log of Modulus (Dynes/cm<sup>2</sup>) vs. Temperature (°C) of Extruded HDPE

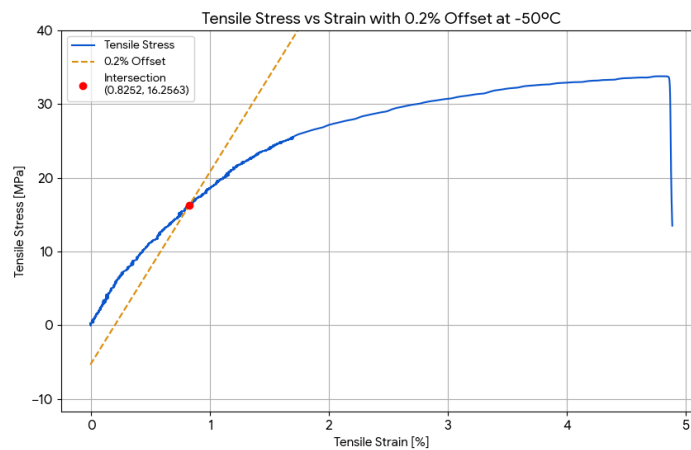
The sharp decline in Young’s Modulus near HDPE’s melting temperature (125°C) is characteristic of semi-crystalline polymers. From figures 3 and 5, we can see that the mechanical properties of HDPE are significantly degraded, and a full stress and strain test was not achievable. This is due to the testing temperature being too close to HDPE’s melting temperature, so the dogbone was in the viscous stage, not the rubbery region.

Figure 6 shows the Young’s modulus for -100 °C being lower than at -80 °C. Since HDPE’s glass transition temperature is a little below -100 °C, HDPE should only become stiffer and stronger as temperatures go from -80 to -100 °C. We can attribute this unusual behavior to not having enough data since only one sample was tested at each temperature, which is not statistically significant. An additional explanation for this result is the possibility that the extruded dogbone for the -100 °C test was cut in the transverse direction. This leads to a significant reduction in strength as the chains are not oriented along the length of the dogbone.

*Table 4: Ductility and Ultimate Tensile Strength vs Temperature for extruded samples*

Temperature (°C)	-100	-80	-50	20	125
Ductility (%)	4.11	3.99	4.89	N/A	N/A
UTS (MPa)	27.53	34.02	33.78	25.31	N/A
Yield Strength (MPa)	12.37	13.63	16.26	12.43	N/A

Ductility was calculated for the three samples that failed by finding the maximum strain at failure. HDPE’s ductility is very temperature dependent and table X highlights its brittle behavior at low temperatures. The instron was stopped before the samples failed at room temperature so ductility was not computable. Ultimate Tensile Strength was calculated using the maximum function on Excel. Lastly, the Yield Strength was obtained by using the 0.2% offset method and the slope of the linear-elastic region as shown in the figure below.



*Figure 7: 0.2% offset method for calculating Yield Strength on Extruded HDPE*

For the same reasons described above, ductility and UTS were not measurable at 125°C. It is important to acknowledge significant limitations in the experimental methodology that may affect the reliability and statistical validity of the reported results. ASTM D638 standards recommend testing a minimum of five specimens at each test condition to establish statistically meaningful average values and to assess data variability through standard deviation calculations [17]. However, due to time and resource constraints, only a single specimen was tested at each temperature condition in this study. This limited sample size prevents proper statistical analysis and makes it impossible to determine whether the measured properties represent typical behavior or outlier values that may have resulted from specimen-specific defects, machining irregularities, or testing anomalies

## Discussion

### Temperature Impacts

From the results of the variable-temperature tensile testing, HDPE was identified as a semi-crystalline polymer. A marked collapse in mechanical properties was observed at 125°C, characteristic of the melting range of semicrystalline polymers, where the crystalline regions become mobile [25]. Amorphous polymers do not have this characteristic decline at their melting temperatures. As no values above the 125°C sample were taken, the melting temperature of HDPE was confirmed with outside literature differential scanning calorimetry data, as seen below [25]. The uptick in energy release corresponds to the phase change as HDPE becomes liquid, hitting its peak at around 132°C.

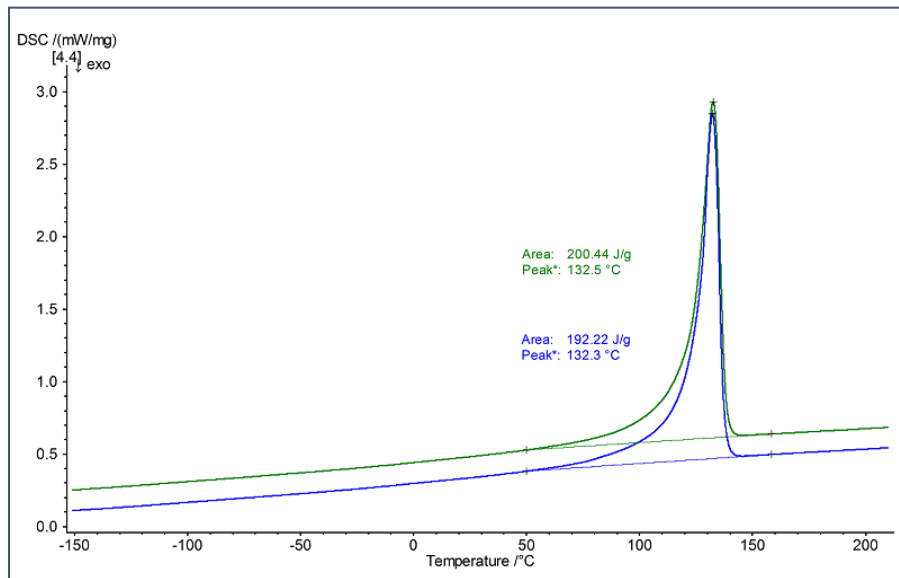


Figure 8: DSC identification of melting temperature of HDPE [25]

A temperature range of -100°C to 125°C was tested, or a range from around the expected glass transition temperature to the expected melting temperature. As temperature rose, the secondary bonds within HDPE broke, allowing mobility within the amorphous regions of the polymer, increasing ductility, and decreasing tensile strength [26]. The greatest ductility was shown with the 20°C (room temperature) sample, the conditions at which HDPE is typically used.

While testing more samples at lower temperatures was not within the scope of this lab, it would have allowed for the identification of HDPE's glass transition temperature. As seen in Figure 9, the glass transition temperature is noticeable from the drastic change in slope of the Elastic modulus— placing pure HDPE's glass transition temperature at around  $-120^{\circ}\text{C}$  [26].

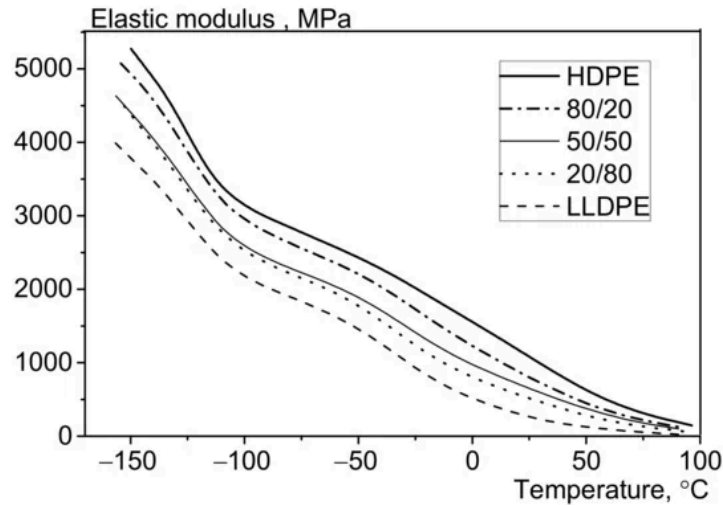


Figure 9: Temperature vs. Elastic Modulus of HDPE & LLDPE Composites [26]

### 3D Printing Impacts

While there was not the opportunity to test 3-D printed samples of HDPE in this lab, it is still important to consider the impacts of the process on HDPE's properties under tensile loading. One important processing factor is print direction; if a print pattern is laid parallel to the load direction, or the  $0^{\circ}$  direction, the stiffness, strength, and elongation ranges can be similar to that of injection molded or extruded HDPE samples [27]. By contrast, a perpendicularly-laid pattern causes delamination, as the bonding strengths between strands and layers is significantly lower to the tensile strengths within the material itself.

As seen in Figure 10, Injection molding reaches about 360% elongation, while FFF in the ( $0^{\circ}$  direction reaches about 90-380% elongation and the  $90^{\circ}$  direction reaches only about 15-140%. These elongation ranges are further defined by the nozzle size of the FFF/ FDM printer. A smaller nozzle size creates smaller gaps between layers, improving interlayer diffusion and increasing density for a greater percent elongation [27].

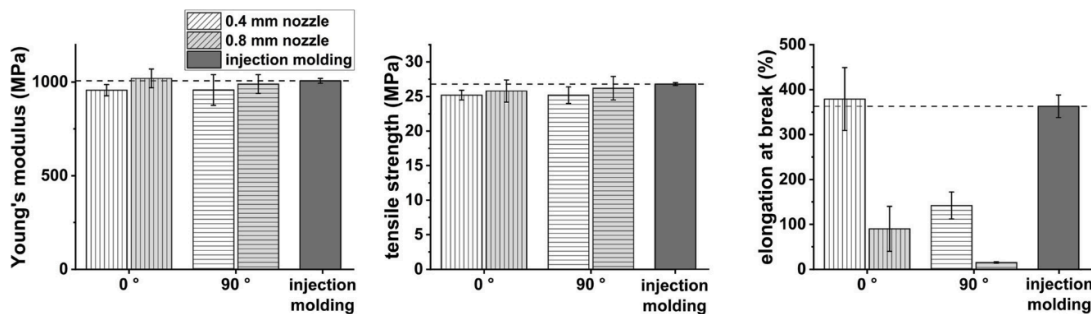


Figure 10: Mechanical properties of HDPE varying with processing factors [27]

Some other important factors for a print with improved mechanical properties are a slower print speed, a greater percent infill value, and infill cross-section geometry and alignment [27]. HDPE also has a few additional key struggles with the FDM printing process due to its higher melting temperature, greater crystallinity, and lower surface energy than other commonly used print filaments. This high print temperature comes with a more rapid heat drop as the print layers and part cools, which causes shrinking post printing, potential warpage, poor bed adhesion, and poor diffusion between the layers. HDPE used to be a common print filament but has become less widespread with the rise of PLA. HDPE composites are being explored to solve the adhesion problems [27].

## **Injection Molding and Extrusion Impacts**

The experimental results revealed that injection molded HDPE specimens exhibited significantly lower mechanical properties compared to extruded specimens tested at room temperature [28, 29]. At 20 °C, the extruded specimens demonstrated an elastic modulus of 1.21 GPa, whereas the injection molded specimens showed a modulus of only 0.80 GPa, representing a 34% reduction in stiffness. This substantial difference in mechanical performance can be attributed to multiple contributing factors related to both processing defects and fundamental differences in microstructural development between the two manufacturing methods.

The primary cause of reduced strength in the injection molded specimens was improper material preparation and processing control [28]. The HDPE pellets were not adequately dried prior to injection molding, allowing moisture absorption from atmospheric exposure. When these moisture-laden pellets entered the heated barrel of the injection molding machine, the absorbed water rapidly vaporized and created steam bubbles within the polymer melt. These vapor pockets were then injected into the mold cavity along with the polymer, resulting in incomplete cavity filling and insufficient packing pressure. The manifestation of this defect was clearly visible as a concave depression along the centerline of the dogbone gauge section, indicating internal voids and inadequate material consolidation. Such voids act as stress concentrators during mechanical testing, initiating premature failure and reducing the effective load-bearing cross-sectional area of the specimen.

Beyond the processing defects, fundamental differences in crystallinity between the two manufacturing methods contributed to the observed property variations. Extruded HDPE exhibits the highest crystallinity at 75.2%, compared to 67.6% for injection molded specimens and 56.1% for compression molded specimens [29]. This 7.6% difference in crystallinity has a direct and significant impact on mechanical properties. Research by Addiego et al. demonstrates that yield stress and lamella thickness are proportional to crystallinity and increase linearly with the crystallinity index [29]. The higher crystallinity in extruded specimens results from the continuous cooling process during extrusion, which allows for more extensive chain alignment and crystalline structure development. The enhanced crystalline regions provide a stronger “backbone” structure that resists deformation, leading to higher elastic modulus and yield strength values.

The geometric discrepancy between specimen types further complicated direct comparison and contributed to apparent weakness in the injection molded samples. While the extruded specimens conformed to ASTM D638 Type I geometry with a gauge section width of 0.5 inches, the injection molded specimens had a reduced width of only 0.25 inches. This 50% reduction in cross-sectional area,

when combined with internal voids from improper packing, substantially diminished the load-bearing capacity of the injection molded specimens [28]. The smaller cross-section also meant that any processing defects had a more pronounced effect on overall mechanical performance, as there was less material volume to distribute stress around void regions.

Thickness effects and molecular orientation differences between processing methods also played a role in the observed property variations. Literature findings indicate that injection molded specimens with 4 mm thickness exhibit approximately 23% higher elastic modulus than 2 mm specimens, attributed to differences in molecular orientation through the thickness [28]. In injection molding, polymer chains near the surface experience higher shear rates and cooling rates, leading to greater molecular alignment in the flow direction compared to the core region. However, this orientation benefit is offset when processing defects are present. The presentation data showing that extruded specimens achieved a yield stress of 29.5 MPa at room temperature, compared to lower values for injection molded specimens, reflects both the higher crystallinity and the absence of processing-induced defects in the extruded material [29].

The effect of improper packing extends beyond simply creating voids within the material. Insufficient packing pressure during injection molding prevents the polymer chains from being compressed and oriented optimally within the mold cavity, resulting in a less dense material with reduced intermolecular interactions and weaker secondary bonding between polymer chains [28]. Research has shown that higher mold temperatures and proper packing pressure lead to improved modulus in injection molded parts by allowing more complete crystallization and better molecular organization. The caved-in appearance of the injection molded specimens indicates that the melt did not maintain sufficient pressure during cooling and solidification, allowing the material to shrink away from the mold walls and creating internal stress concentrations.

Additionally, the regrind effect suggests that multiple thermal histories can slightly improve stiffness and strength properties, likely due to molecular chain alignment during repeated processing. However, this benefit was not realized in the current injection molded specimens due to the overwhelming impact of moisture contamination and improper processing parameters [28]. The combination of reduced crystallinity, geometric constraints, moisture-induced voiding, and inadequate packing pressure created a compounding effect that resulted in mechanical properties substantially below those of properly processed extruded HDPE. These findings underscore the critical importance of proper material preparation, including adequate drying of hygroscopic polymers, and careful control of processing parameters to achieve optimal mechanical performance in injection molded components [28, 29].

## **Conclusion**

This investigation demonstrated how strongly the mechanical performance of HDPE depends on both temperature and processing history, reinforcing its classification as a semi-crystalline polymer whose properties are governed by molecular mobility and crystalline morphology. Tensile testing across a broad temperature range captured the expected transitions: brittle, high-modulus behavior at low temperatures; peak toughness near room temperature; and a sharp collapse in strength and stiffness as temperatures approached the melting regime. These results align with established literature on HDPE's glass transition and melting behavior, confirming the temperature-driven mechanisms that dominate its deformation and failure.

The comparison between extruded and injection-molded specimens highlighted the profound influence of processing on microstructure and mechanical performance. Extruded samples displayed significantly higher modulus and strength due to their higher crystallinity and consistent geometry, whereas injection-molded samples exhibited reduced properties primarily because of moisture-induced voiding, inadequate packing pressure, and reduced gauge-section dimensions. These findings emphasize that even small deviations in processing conditions—such as insufficient pellet drying—can severely compromise part quality and obscure the true effects of the manufacturing method.

However, several limitations constrained the strength of the conclusions. Only a single specimen was tested at each temperature, preventing statistical validation and making the results sensitive to specimen-specific defects. Some samples, particularly at elevated temperatures, could not be fully characterized due to premature softening or test setup constraints. These limitations underscore the need for broader sample sets, improved control of processing variables, and additional testing modalities (e.g., DSC, microscopy) to more fully link thermal transitions, crystallinity, and mechanical performance.

Overall, the study reinforces key engineering principles: polymers are highly sensitive to their thermal environment, their processing route, and even subtle preparation steps. Understanding these interactions is essential for selecting the correct grade, manufacturing process, and operating conditions for HDPE in real-world applications. Future work should expand specimen quantity, incorporate 3D-printed samples, and explore quantitative microstructural analysis to more deeply connect processing, structure, and properties.

## **Reflection**

We used our knowledge of polymer microstructure and how temperature affects bond strength to think critically about the various stress and strain curves obtained using the Instron machine at various temperatures (stronger and stiffer chains as temperatures trend towards HDPE's glass transition temperature, more ductile since chains can slide at higher temperatures).

We also used our class knowledge of polymer processing and manufacturing to investigate why the injection molded samples were degraded and so the data was not accurate to HDPE properties.

Mostly, we found that the data was in line with our expectations based on HDPE literature. However, the test run at  $-100^{\circ}\text{C}$  did not fit the trend we expected for properties near the glass transition temperature. Ideally, we would've wanted to test 3-5 samples at each temperature to average out inconsistencies in the sample preparation and hopefully see data exactly consistent with polymer theory.

We would've also liked to have more time to be able to perfect the injection molding process in order to have useful testing data to compare to extruded samples. On top of that, it could have been interesting to 3D print HDPE dogbones to compare this manufacturing method's effects on mechanical properties.

Another aspect of these tests that we would have liked to improve upon would be to test HDPE at a few temperatures below its glass transition temperature to be able to truly validate the location of HDPE's glass transition temperature ourselves. Similarly, we would have liked to test HDPE in its rubbery region.

## References

- [1] Pars Ethylene Kish. *Chapter 1: History and Physical Chemistry of HDPE*.
- [2] National Historic Chemical Landmark. *Polypropylene and High-Density Polyethylene*. American Chemical Society.
- [3] Tedium. *HDPE History: It Started With Hula Hoops*. May 26, 2024.
- [4] M. Hall, "HDPE Recycling," *Business Waste*, 20-Jun-2023. [Online]. Available: <https://www.businesswaste.co.uk/your-waste/plastic-recycling/hdpe-recycling/> [Accessed: 29-Nov-2025].
- [5] Alfa Chemistry. "High-Density Polyethylene (HDPE): A Comprehensive Scientific Overview." *Alfa Chemistry*, 2024.
- [6] Laird Plastics. "HDPE Guide: Properties, Uses & Applications 2025 Update." *Laird Plastics*, 2025.
- [7] Protolabs. "Glass Transition Temperature ( $T_g$ ) of Polymers." *Protolabs*, 2024.
- [8] Tangent Materials. "5 Common Commercial Applications of HDPE." *Tangent Materials*, 2021.
- [9] Ican Group. "Practical Uses of HDPE: From Industry to Daily Life." *Ican Group*, 2025.
- [10] Piedmont Plastics. "HDPE Plastic: Common Uses & Applications." *Piedmont Plastics*, 2021.
- [11] R. Azad and H. Shahrajabian, "Experimental study of warpage and shrinkage in injection molding of HDPE/rPET/wood composites with multiobjective optimization," *\*Materials and Manufacturing Processes\**, vol. 34, no. 3, pp. 274–282, 2018, doi: 10.1080/10426914.2018.1512123.
- [12] N.-y. Zhao, J.-y. Lian, P.-f. Wang, and Z.-b. Xu, "Recent progress in minimizing the warpage and shrinkage deformations by the optimization of process parameters in plastic injection molding: a review," *Int. J. Adv. Manuf. Technol.\**, vol. 120, no. 1–2, pp. 85–101, Feb. 2022, doi: 10.1007/s00170-022-08859-0.
- [13] ExxonMobil Chemical, "High-Density Polyethylene (HDPE) Product Overview." [Online]. Available: <https://www.exxonmobilchemical.com/en/products/polyethylene/hdpe>. [Accessed: 29-Nov-2025].
- [14] MatWeb, "HDPE Material Data Sheet." [Online]. Available: <https://matweb.com/search/datasheet.aspx?MatGUID=9d266b41e81f4ea28bf54718fe4c40af>. [Accessed: 29-Nov-2025].
- [15] S. Melito, "Extrusion Molding vs. Injection Molding," *Fictiv*, 19-Sep-2024. [Online]. Available: <https://www.fictiv.com/articles/extrusion-molding-vs-injection-molding>. [Accessed: 29-Nov-2025].
- [16] "HDPE Guide," ME114 Course Materials, Tufts University, document ME114;HDPE guide.docx.

- [17] ASTM D638-14, "Standard Test Method for Tensile Properties of Plastics," ASTM International, West Conshohocken, PA, 2014.
- [18] S. Carias, personal communication, Dec. 2025.
- [19] ASTM D3039, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials," ASTM International, West Conshohocken, PA, 2002.
- [20] Instron, "A Guide to Selecting the Right Extensometer," Instron White Paper, Norwood, MA. [Online]. Available: <https://www.instron.com> [Accessed: 29-Nov-2025]
- [21] Instron, "5800 Series Universal Testing Systems Operator's Manual," Instron Corporation, Norwood, MA, 2015.
- [22] Instron, "Environmental Chambers for Materials Testing," Instron Technical Literature, Norwood, MA. [Online]. Available: <https://www.instron.com> [Accessed: 29-Nov-2025]
- [23] L. C. E. Struik, "Physical aging in plastics and other glassy materials," *Polymer Engineering & Science*, vol. 17, no. 3, pp. 165-173, 1977.
- [24] A. J. Peacock, *Handbook of Polyethylene: Structures, Properties, and Applications*. New York, NY: Marcel Dekker, 2000.
- [25] NETZSCH Polymers, "PE-HD: Polyethylene high density," *polymers.netzsch.com*, 2025. [Online]. Available: <https://polymers.netzsch.com/Materials/Details/8>
- [26] I. Salakhov et al., "Low-Temperature Mechanical Properties of High-Density and Low-Density Polyethylene and Their Blends," *Polymers (Basel)*, vol. 13, no. 11, p. 1821, May 2021, doi: 10.3390/polym13111821.
- [27] C. G. Schirmeister, T. Hees, E. H. Licht, and R. Mülhaupt, "3D printing of high density C. G. Schirmeister, T. Hees, E. H. Licht, and R. Mülhaupt, "3D printing of high density polyethylene by fused filament fabrication," *Additive Manufacturing*, vol. 28, pp. 152–159, Aug. 2019, doi: 10.1016/j.addma.2019.05.003.
- [28] M. Amjadi and A. Fatemi, "Tensile Behavior of High-Density Polyethylene Including the Effects of Processing Technique, Thickness, Temperature, and Strain Rate," *Polymers*, vol. 12, no. 9, p. 1857, Aug. 2020. (injection molding)
- [29] F. Addiego, A. Dahoun, C. G'Sell, J.-M. Hiver, and O. Godard, "Effect of microstructure on crazing onset in polyethylene under tension," *Polymer Engineering & Science*, vol. 49, no. 6, pp. 1198–1205, 2009, doi: 10.1002/pen.21194. (extrusion)