School of Engineering
Institute of Materials
Laboratory of Macromolecular
and Organic Materials (LMOM)

Polymer Science (MSE-360)

Injection Molding

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Assistant:

Jean Rego (LMOM, MXG 037)

jean.rego@epfl.ch

Introduction

Commented [MOU1]: Add a DSC section next year to determine crystallinity?

Injection molding is the most widespread technique for mass production of thermoplastic parts. It combines high productivity with excellent reproducibility and the ability to fabricate complex geometries. **The goal of this TP is to introduce the principles of injection molding and to explore how processing conditions affect the structure and properties of polymeric materials.**

To this end, dogbone specimens from poly(L-lactic acid) (PLLA) will be fabricated under conditions that yield either a fully amorphous or a semi-crystalline morphology. These specimens will then be mechanically tested in tension at room temperature and at elevated temperature. The results will be compared to dogbones made from polycarbonate (PC), an amorphous engineering thermoplastic with high glass transition temperature.

This will allow us to connect the processing history with differences in microstructure (amorphous vs. semi-crystalline, strain-induced crystallization, etc) and mechanical behavior (yielding, crazing, brittle vs. ductile response).

Background

1. Polymer Processing and Structure

The performance of thermoplastics depends not only on chemical structure but also on **processing history**, which controls morphology:

- **amorphous polymers** (e.g. PC, amorphous PLLA) are transparent, isotropic, soften abruptly at the glass transition temperature T_g.
- **semi-crystalline polymers** (e.g. semi-crystalline PLLA) contain crystalline lamellae embedded in an amorphous matrix. Polymer like polyethylene and polypropylene with low T_g can only be used as solid materials because of their semi-crystalline nature.

Key structural features influencing processing:

- **chain rigidity**: higher rigidity increases T_g, melt viscosity, and slows down crystallization.
- **molar mass**: higher molar mass increases strength, impact resistance (ductility), and viscosity, but decreases chain mobility and crystallization rate.
- **chain branching**: reduces crystallization rates (e.g. in low-density polyethylene (LDPE) compared to high-density polyethylene (HDPE)) and increases viscosity; enhances "melt strength", which is beneficial for processes requiring significant elongational deformation, such as fiber spinning and foaming.
- **additives/nucleating agents**: accelerate crystallization to ensure solid-like behavior, tune microstructure and spherulite size to adjust mechanical properties and optical appearance.

Dr. Daniel Görl
+41 21 693 78 65
daniel.gorl@epfl.ch
lmom.epfl.ch

2. Injection Molding

Injection molding is the most widely used processing technique for **thermoplastics**, enabling the mass production of parts from a few grams to several kilograms with **high precision and repeatability**. Applications range from automotive and electronics to aerospace, household appliances, packaging, and medical devices.

Compared to other processing techniques such as extrusion or thermoforming, injection molding offers a much **higher degree of design freedom**. It allows the production of parts with excellent dimensional accuracy, smooth surface finish, and complex geometries that would be difficult or impossible to achieve otherwise. Thin walls, fine details, or integrated functions such as hinges and click-fits can be realized in a single step. **Importantly, the process is not limited by materials choice**: amorphous polymers, semi-crystalline polymers, polymer blends, and filled systems can all be molded effectively. Combined with the possibility of very high production rates, this makes injection molding one of the most cost-efficient technologies for large-scale manufacturing.

Nevertheless, the technique also presents significant challenges. Tooling is expensive, especially the design and fabrication of molds, which must withstand high pressures and thermal cycles. Energy consumption per cycle is relatively high, and the process is sensitive to parameters such as temperature, pressure, and cooling rate. Improper settings can lead to warpage, shrinkage, or other cooling-induced defects. Furthermore, injection molding is not always well-suited for processng fiber-reinforced composites, where maintaining fiber orientation and preventing damage during injection can be particularly difficult.

The Injection Molding Cycle

Commented [MOU2]: Exam question: which polymer would you use for injection molding. Let them choose between an amorphous and a semicrystalline one.

An injection molding machine is composed of three main units: first, the **plasticizing unit** based on an extruder which includes the screw, barrel, and heaters melts and homogenizes the polymer pellets. Second, **the mold**, which defines the shape of the final part, must withstand the high injection pressures while also enabling controlled cooling and reliable ejection of the molded article. Third, the **clamping system** keeps the two halves of the mold tightly closed during injection and controls mold opening for ejection. Machines are typically specified by their injection volume (cm^3) and their clamping force (tons). For instance, a "90/20" press would provide an injection volume of 90 cm^3 and a clamping force of 20 tons.

The injection molding process follows a repeating cycle that can be divided into three main stages (Figure 1):

- **plasticizing**: polymer pellets are fed into the barrel of the extruder and melted by the combined action of heating and the screw rotation. As the material accumulates, a reservoir of homogenized, molten polymer builds up in front of the screw.
- **injection & packing**: once the required shot size is reached, the screw moves forward hydraulically and forces the molten polymer into the mold cavity under high pressure. After the cavity is filled, additional pressure is applied during the holding phase to compensate for shrinkage as the material begins to cool and solidify.
- **cooling & ejection**: the part solidifies against the cold mold walls. Once it is sufficiently rigid, the mold opens and ejector pins push the part out, making the mold ready for the next cycle.

Dr. Daniel Görl
+41 21 693 78 65
daniel.gorl@epfl.ch
lmom.epfl.ch

The cycle time is one of the key parameters in injection molding because it directly determines productivity. For small, thin-walled parts, cycle times can be as short as a few seconds, whereas large or thick-walled components may require several minutes. Importantly, cooling is usually the rate-limiting step of the cycle: while plasticizing and injection take only a fraction of the total time, the polymer must remain in the mold long enough to solidify without warping or deformation. For semi-crystalline polymers, the cooling step also controls the degree of crystallinity, which strongly influences mechanical performance.

Mold design (e.g. introducing efficient cooling channels and proper gating) is therefore just as important as machine settings: a well-designed mold can drastically reduce cycle times and improve both part quality and dimensional stability.

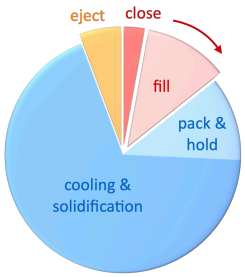

Fig. 1. The injection molding cycle is determined by cooling and materials solidification.

Key Processing Parameters

Successful injection molding requires careful adjustment of several machine and mold parameters:

- **extruder temperature**: if set too low (close to the melting temperature), the polymer may not fully melt, leading to incomplete filling. If too high, thermal degradation can occur (many polymers require extrusion temperature around 200 °C or higher).
- **screw rotation speed and design**: these determine the homogenization efficiency and the amount of molten polymer available for injection (shot size).
- **mold temperature**: affects cooling rate, surface finish, and (for semi-crystalline polymers) crystallinity, which strongly impacts mechanical properties.
- **injection pressure and speed** control how the molten polymer fills the cavity. Too slow filling can cause premature solidification and incomplete filling due to clocking. Too fast filling may cause flash, jetting, or high internal stresses.
- **holding pressure and time** compensate for volumetric shrinkage during cooling. Insufficient holding can result in sink marks or voids.
- **cooling efficiency**: determines both cycle time and dimensional stability of the molded part. Efficient cooling channels and uniform wall thickness are critical for consistent quality.

Challenges and Defects

Despite its versatility, injection molding presents several challenges that engineers must anticipate:

Dr. Daniel Görl
+41 21 693 78 65
daniel.gorl@epfl.ch
lmom.epfl.ch

- **high mold cost**: precision molds, typically made from hardened steel, are expensive (ranging from hundreds to thousands of CHF). This makes injection molding cost-effective primarily only for large series production.
- **cooling stresses**: since the surface cools faster than the core, residual stresses may develop, leading to warpage or even cracking.
- **shrinkage and sink marks**: volume contraction during cooling and crystallization can produce visible depressions unless adequately compensated during the packing phase.
- **weld lines**: when two flow fronts meet, a weak interface forms, often visible as a line on the surface and potentially reducing mechanical strength.
- **air entrapment**: if venting is insufficient, trapped air can prevent proper filling or cause local burning. Proper vent design, often near weld lines, is essential.
- **wall thickness variations**: sudden transitions from thick to thin sections promote uneven cooling, residual stress buildup, and stress concentration points.
- **material sensitivity**: amorphous polymers (e.g. PC, PMMA) are primarily limited by their T_g, whereas semi-crystalline polymers (e.g. PA, PLLA) are additionally influenced by cooling rate and crystallization kinetics.

Mold Design Considerations

The mold is the heart of injection molding, defining not only the geometry of the part but also the efficiency and quality of the process. Because it must withstand very high pressures during injection (typically 400-500 bar, corresponding to several tons of clamping force, but potentially reaching thousands of tons for large machines), molds are usually made of hardened or pre-hardened steel. Their internal surfaces are precisely machine by milling or EDM, then finished through polishing or plating (e.g. hard chrome) to achieve the required dimensional accuracy and surface appearance.

Molds represent a major cost factor in injection molding and are only economically justified when amortized over large production series. Alternatives such as aluminum or even epoxy molds exist, but they offer limited durability and reduced part quality, typically surviving only a small number of production cycles.

The mold closing system locks the moving and fixed halves together during injection. Its strength and precision are critical, as any mismatch under pressure leads to flash or dimensional errors. Beyond strength, good mold design must also consider:

- injection points (gates): their placement determines how the cavity fills. Poorly positioned gates can cause weld lines or orient stresses in critical regions.
- cooling channels: efficient and uniform cooling reduces cycle time and minimizes warpage or residual stresses.
- ejector systems: parts must be removed cleanly and without damage; ejector pins or plates must be carefully positioned.
- surface finish: the machining and polishing of mold surfaces directly influence the appearance, gloss, and even demolding behavior of the molded product.

Dr. Daniel Görl
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daniel.gorl@epfl.ch
lmom.epfl.ch

In summary, **mold design is a delicate balance of mechanical precision, thermal management, and ease of demolding.** The cavity must be filled completely before the polymer solidifies, while still allowing the finished part to be ejected without damage. The placement of cavities, gates, integrated cooling circuits, and ejectors is critical: poor layout can lead to defects such as sink marks, weld lines, voids or cracks. Because of these complexities, mold design has evolved into a specialized engineering field, increasingly supported by simulation software that predicts filling patterns, cooling efficiency, and potential defect formation. Such tools enable mold makers to optimize both part quality and production efficiency before the first tool is even manufactured.

Experimental Part and Discussion

The goal of this TP is to fabricate tensile test specimens (dogbones) via injection molding. By carefully adjusting molding conditions, it is possible to obtain dogbones with different microstructures: fully amorphous or semi-crystalline PLLA. These differences in morphology strongly affect mechanical performance. To make this connection tangible, the specimens will be mechanically tested and compared to polycarbonate (PC), a purely amorphous engineering thermoplastic.

Preparation:

Before the TP, read these instructions and the suggested literature to understand and prepare to discuss:

- Why PLLA can be either amorphous or semi-crystalline depending on processing.
- What is strain-induced crystallization and under what conditions can it occur in PLLA?
- Which specimens (PC, amorphous PLLA, semi-crystalline PLLA) do you expect to be the most ductile/brittle at room temperature and at elevated temperature? Justify.
- Which mold temperature would you choose to fabricate the envisaged materials?
- How do amorphous PLLA and PC differ in their deformation mechanisms and mechanical response? Which microstructural features explain these differences?

These questions should also be addressed in the discussion section of the protocol.

Tasks:

1. **Injection Molding of PLLA Dogbones:**
    - **amorphous PLLA**: produce at least 6 functional dogbones by choosing appropriate extruder conditions, molding temperature, and cooling time.
    - **semi-crystalline PLLA**: produce at least 6 functional dogbones by adjusting the injection-molding conditions accordingly and using 1 wt% of of isopentyl-BTA as a nucleating agent.
    - label specimens clearly
    - take photographs comparing representative dogbones.
2. **PC reference:**
    - since changing material in the extruder requires extensive cleaning, pre-prepared PC dogbones will be provided.

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3. **Tensile Testing:**
    - Test three dogbones for each material in tensile deformation at room temperature.
    - Test three dogbones from amorphous and semi-crystalline PLLA at 80 °C.
    - Use 5 mm/min crosshead speed, 5 kN load cell.
    - For high-temperature tests, equilibrate specimens at 80 °C for 10 minutes in the chamber before testing.
    - Take photographs and/or videos of specimens during and after testing.
    - Note and report any whitening, necking, or brittle failure.

Report Guidelines:

- **processing-structure-property relationships**: explain in detail how molding parameters affected the microstructure and how this translated into mechanical properties.
- **methods**: describe instruments, sample preparation, and tensile testing protocol.
- **detailed conditions**: injection molding settings, conditioning times, and test parameters.
- **photographs** of representative dogbones before and after testing. Discuss optical differences (transparency, whitening, etc.).
- **mechanical analysis**: plot stress-strain curves and report Young's modulus, yield strength, ultimate tensile strength, elongation-at-break, and work-at-break. Provide averages with standard deviations.
- **additional characterization**: propose other technique(s) to distinguish amorphous and semi-crystalline PLLA, and predict expected outcome.
- **discussion**: connect processing history to structure and tensile response; explain strain-induced crystallization, compare ductility vs. brittleness, yielding vs. crazing.
- **nucleating agent**: discuss the role of the nucleating agent in promoting crystallization and how it affects microstructure and mechanical response.
- **conclusion**: summarize key insights.

Safety and practical notes:

- **hot equipment**: barrels, mold, and nozzle are hot. Use protective gloves and follow lab safety.
- **nucleating agent**: although structurally related to FDA-approved compounds, its hazardous properties are not fully known. Handle with gloves and safety glasses.
- **high pressures**: injection machines operate under high clamping and injection pressures. Only trained personnel may program/operate the press. Students observe or assist only under TA instructions.

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Additional Reading

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These documents are available for download on the Moodle page.