Preliminary Assessment of NIU Die Design and Fermilab/NICADD Extrusion

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NIU Extrusion Simulation Limitations/Simplifications

1. Does not include polymer viscoelastic properties, important for free-surface die swell
2. Does not include realistic normal stress (pulling force) at the end of free surface region
3. Does not include gravity force
4. Does not include flow, cooling and solidification, and vacuuming in the calibrator
5. Does not include post-calibrator solidification, cooling and downstream drawing.
6. Does not include dynamic variations in melt temperature and pressure, and in other properties and process-parameters' variations and inconsistencies.

Extrusion process essentials

- It is not possible to make a good die design without full comprehension of melt properties and complete extrusion process

  (Melt properties and PoliFLOW alone will not do it!)

Extrusion process essentials (2)

- It is not possible to make a good extrudate profile without full comprehension of complete extrusion process

  (good die alone will not do it**!)**

Extrusion process essentials (3)

- **It is possible** to achieve a good quality and dimensions of extrudate final product, **especially** with well equipped and instrumented extruder in Fermilab

For precise and good quality of extrudate final profile,

- It is **required, but not enough** to have well-designed die only.
- Particularly in **hollow-profile** extrusion, **calibrator design** with proper vacuuming and cooling is **the most critical** (our case), and
- over-all extrusion process control is always very important (see below).

Extrusion processes are very complex:

- mixing and feeding stock,
- compression, heating-and-cooling, and melting,
- die-flow with free-surface with swelling and pre-drawing,
- Vacuum-calibration and sizing with cooling and solidification,
- drawing and post-cooling, etc.,

so it is **not possible**

… to exactly reproduce previous expert parameters

(expert recipe may help, but is never reproducible and must be readjusted/tweaked)

Even small perturbations

… in properties and process control parameters

(always present due to variations in polymer properties and instrumentation and actuators limitations and uncertainties) **may and will produce extrudate final product deficiencies, and must be readjusted/compensated**.

Only if the over-all extrusion process is fully understood,

- meaning that influence of all controlling parameters on final product quality and dimensions is investigated and quantified,
- it will be possible to set up and well-control extrusion process, in addition to the well-designed die, and quality of the extruder components, instrumentations and control software.

It is well-known,

… that extrusion product quality depends on an operator-skills among others

(experienced with Itasca Plastics)

Therefore, the following is assessment of **significance level**

… or importance and criticality of the three main extrusion-quality contributors for **precise hollow-profile** extrudate:

1. **Die design (significance 8/10)**
2. **Calibrator design (significance 9/10)**:
3. **Extrusion process control (significance 8/10)**

Die design
(**significance 8/10**):

- to balance the melt flow into desired profile and/or to provide optimal melt flow-feed into the calibrator, accounting for extrudate die swell and drawdown to calibrator in the free-flow region).

Calibrator design
(**significance 9/10**):

- for hollow profile (our case), proper design of **calibrator** shape and cooling is very important for solidification and getting final dimensions (cooling rate control, shape guide control - iterative process is necessary due to coupled nature of complex cooling, solidification and sizing).

Extrusion process control
(**significance 8/10**):

- Tweaking-tuning proper extrusion process set-up (tuning all parameters: melt temperature, pressure and flow rates, calibration with cooling and vacuuming, balancing the take-up puller speed, etc.). Screw RPM dictates melt flow rate and pressure, residence time, degradation and die swell. Take-up puller speed dictates calibrator starvation or stuffing (even choking), drawdown, etc. With vacuum calibration the vacuum levels (and/or positive pressure levels in hollows) are coupled with mass flow exiting extruder and take-up speed.

Some other comments

- Unlike injection molding, extrusion process is very sensitive (hard to achieve precise dimensions) due to the fact that cooling and final shaping of the extrudate occur virtually under zero gage pressure.

Some other comments (2)

- The product design will dictate the process line speed and shrinkage of the product. It is conceivable that a convex calibrator could help turn an otherwise concave (shrunk) extrudate into a desired flat extrudate.
- The amount of elastic memory the melt has as it exits a converging and die land plates will depend upon the residence time of the melt as it passes through.

Some other comments (3)

- Studies have shown that the die swell achieves a plateau when land length to die gap exceeds 10 or 15.

Some other comments (4)

- Studies also have shown that higher shear stresses at the wall of the die lip also correlate with greater **die swell**. Finally, (as expected) different resins exhibit notably different swells due to viscoelastic properties: Polyethylenes on the high side, PVC low/moderate, and PS/HIPS moderate.

Some other comments (5)

- The 1:2 cm shape of the extrudate is **thick** for a plastic product (thin gap 10-hole die is "easier" in that regard)

Some other comments (6)

- The longer side of the rectangle profile undergoes greater sink (shrinkage) than the shorter side.
- This sink is due to non-uniform cooling and solidification of the extrudate in the calibrator (softer regions will be drawn and sink more). If the profile were a square, then the midpoints between each corner would sink the same amount (see next).

Some other comments (7)

- **The round hole becomes elliptical** (with the major axis parallel to the longer sides) due to the non-uniform shrinkage (sinking) that occurs during the **non-uniform cooling** of the extrudate.
- The problem is a thermal/mechanical one. It is understandable that the flow **simulation shows** an ellipse major axis perpendicular to the longer wall due to the fact the shear rate is greater in this direction, thus more velocity relaxation. This also explains why plates swell more in the thickness direction than the width direction.

Preliminary Suggestions for NIU Die and Calibrator Designs

1. The optimum design of both, die and calibrator is necessary for precise hollow-profile extrudate
2. Full comprehension of all extrusion processes and polymer properties are necessary for proper modeling and simulation, and particularly for die and calibrator design.
3. Full understanding of software features and limitations is critical, and proper testing against well-established results is necessary
4. Simplifications in modeling and limitations of simulations should be stated and experimentally verified
5. Knowing full set of polymer properties and Polyflow simulations are not enough for die and calibrator design as sometimes believed.
6. The design should provide for necessary process-parameters adjustments for minimizing observed product deficiencies during extrusion, since simulation alone cannot be all-inclusive.
7. After die fabrication, bad die may be identified, but good die will not make good product without a good calibrator and good extrusion process control.
8. However, with a good die and calibrator, and with good extrusion process control, it is possible to achieve a good quality and dimensions of extrudate final product, especially with well equipped and instrumented extruder in Fermilab.

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Fermilab/NICADD extrusion facts:

1. 77 hrs total extruder running time in about 6 months (only couple of hours provided for our experimentation).
2. Systematic and detailed record not kept/available (not available to me).
3. Not giving due priority to fully comprehend and investigate complex thermo-mechanical extrusion processes, since it is very critical to achieve objectives (die and calibrator design and process control).
4. Partial solutions sought to quickly cure the symptoms as they develop, but not to cure the "disease."
5. Belief that sophisticated equipment and expert recipe will make excellent product.

Preliminary Suggestions for Fermilab/NICAD Systematic Extrusion Testing

1. Systematic investigation of all critical control-parameters' influence on final product quality and dimensions are necessary.
2. Detailed record of all settings and accurate timings must be done, as well as qualitative descriptions of all observed phenomena, including preliminary comments and justifications.
3. Deviations (perturbations) from "optimal settings" should be investigated to confirm or reject preliminary hypothetical justifications.
4. Coupling (complementing/opposing) parameters should be varied together to complement or compensate mutual influences.
5. Easier-to-control parameters should be changed to investigate optimum mass-rate, pressure or cooling balances.
6. For example, take-up puller rate has faster time response than melt feeding rate for mass rate balance in calibrator.
7. Nitrogen gage pressure and vacuum level influence the hole size, etc.
8. Pellet feed-rate and melt gear-pump rate must be balanced, and it could be achieved with different screw speeds, thus pressure and residence time may be changed, which in turn influence melt degradation (optical and viscous properties).
9. Melt temperature should be kept to minimum required (may be lowered)
10. Extruder pressure could be lowered if more consistent feed is achieved
11. Take-up puller speed should be balanced with melt rate to achieve vacuum-sizing in the calibrator and balanced cooling and downstream drawing/stretching.
12. Localized cooling should be balanced to minimize unequal solidification and thermal deformation observed.

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9. **Melt actual temperature should be kept to minimum required (may be lowered from 210 to 200C)**
10. Extruder pressure could be lowered if more consistent feed is achieved
11. Take-up puller speed should be balanced with melt rate to achieve vacuum-sizing in the calibrator and balanced cooling and downstream drawing/stretching.
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9. Melt temperature should be kept to minimum required (may be lowered)
10. **Extruder pressure could be lowered if more consistent feed is achieved (may be lowered from 500 to 250 psi)**
11. Take-up puller speed should be balanced with melt rate to achieve vacuum-sizing in the calibrator and balanced cooling and downstream drawing/stretching.
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8. Pellet feed-rate and melt gear-pump rate must be balanced, and it could be achieved with different screw speeds, thus pressure and residence time may be changed, which in turn influence melt degradation (optical and viscous properties).
9. Melt temperature should be kept to minimum required (may be lowered)
10. Extruder pressure could be lowered if more consistent feed is achieved

11. **Take-up puller speed should be balanced with melt rate to achieve vacuum-sizing in the calibrator and balanced cooling and downstream drawing/stretching.**

12. Localized cooling should be balanced to minimize unequal solidification and thermal deformation observed.

Preliminary Suggestions for Fermilab/NICAD Systematic Extrusion Testing

1. Systematic investigation of all critical control-parameters' influence on final product quality and dimensions are necessary.
2. Detailed record of all settings and accurate timings must be done, as well as qualitative descriptions of all observed phenomena, including preliminary comments and justifications.
3. Deviations (perturbations) from "optimal settings" should be investigated to confirm or reject preliminary hypothetical justifications.
4. Coupling (complementing/opposing) parameters should be varied together to complement or compensate mutual influences.
5. Easier-to-control parameters should be changed to investigate optimum mass-rate, pressure or cooling balances.
6. For example, take-up puller rate has faster time response than melt feeding rate for mass rate balance in calibrator.
7. Nitrogen gage pressure and vacuum level influence the hole size, etc.
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