Vibration Assisted Injection Molding for PLA with Enhanced Mechanical Properties and Reduced Cycle Time

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ABSTRACT

Vibration assisted molding (VAIM) is a process in which vibrational movement is introduced to the injection screw during the injection stage of molding processes. This research was focused on the effect of processing parameters on physical characteristics of poly-lactic acid (PLA) during vibration assisted injection molding (VAIM). In vibration assisted injection molding processes, the travel of the injecting screw is moved back and forth to create an oscillatory motion. The frequency, duration and initiation point of the motion can be individually controlled. It was observed that VAIM based PLA products have higher total crystallinity than conventionally molded PLA products under identical conditions sans the vibration. Based on these results it was hypothesized that the vibration primarily affects the molecular arrangement of the polymer chains which in turn affects the nucleation density and thus the crystallinity. In addition, it was observed that the cycle time can be reduced by at least 25% when vibration was applied.

Keywords: injection molding, VAIM, PLA, crystallinity

1 VIBRATION ASSISTED INJECTION MOLDING (VAIM)

Injection molding processing is one of the most commonly used manufacturing techniques for polymer products. Like all manufacturing techniques, manufacturers aim at reducing time and cost consumed while simultaneously increasing quality standards for injection-molded products[1]. The definition of molding quality is very complex, as it often includes mechanical properties, surface quality, dimensions, and density. As a result, the continued development of this versatile mass-production process has helped extend the applicability, capability, flexibility, productivity and profitability[2]. Achieving superior quality is an effective means of maintaining a competitive stronghold in this business field.

Typical injection molding processes can be divided into four major stages: injection, packing, cooling and ejection.

The injection stage starts with the polymer melt injected into the evacuated mold cavity, which is located on the clamping unit side of the machine. During this stage, the polymer in its liquid state is injected under high pressure through a screw mechanism. The polymer is then forced through a runner system into the mold cavity. In the second stage, the material is packed under a high pressure for a specific amount of time to compensate for volumetric shrinkage and achieve desired dimensional stability in the final product. In the third stage, the polymer in the mold cavity is cooled to ensure the solidification of the melt in the mold cavity. In the final stage, the finished product is ejected from the cavity.

In vibration assisted injection molding (VAIM) the standard injection molding process is augmented with a dynamic oscillatory motion of the injection screw at specific pressures, frequencies, amplitudes, and durations as the melt is packed and solidified. A schematic of this setup is illustrated in Figure 1.

![Figure 1: Schematic of the vibration injection molding setup](image)

VAIM has been reported to promote the molecular orientation of the polymer chain in molded samples[3]. The vibratory effect essentially deforms the polymer as it cools down to temperatures just above its glass transition temperature ($T_g$). Continuing this as the temperature dips below $T_g$, ensures that the induced chain orientation is maintained in the solidified polymer, and chain relaxation...
does not occur. Both the vibration contributed by the oscillatory shearing action (in the melt stage) and to a lesser extent, hydrostatic pressure (as the polymer solidifies) play a role in altering certain aspects of the molded product’s material as well as physical properties. In traditional injection molding, this is not observed since solidification under a quiescent condition would have resulted in relaxation of the oriented polymer chains to form a random coil arrangement. In Figure 2, the colored sections are evidence of high molecular orientation in amorphous PLA dog bone samples.[4]

Figure 2: Optical birefringence pattern on amorphous PLA samples (PLA 3051D) prepared by (A) conventional, and injection molding with oscillatory vibration at (B) 4 Hz for 10s, and (C) 6 Hz for 15s. Melt flow direction is from right to left.

2 MATERIAL SELECTION

Polylactide or Poly(lactic acid) (PLA) is a thermoplastic polymer derived from renewable resources. This is in contrast to common commercial grade thermoplastics, such as those from the polyethylene family, and isotactic polypropylene, that are derived from nonrenewable petroleum reserves. The material is a polyester of lactic acid (C₆H₁₂O₃) that naturally degrades over time when exposed to the environment. PLA is viewed as a favorable substitute to other polymeric materials.

PLA refers to a family of materials which share slightly different characteristics. PLA has two stereoisomers namely the L-lactic and the D-lactic acid. Three forms of PLA are available commercially: pure L-lactide, pure D-lactide, and a mix of L and D-lactide. Relatively pure L-feed and D-feed PLA is referred to as PLLA and PDLA respectively[5]. Common commercial grade PLA (that requires high crystalline content) contains a majority L-feed mixture, and a minimum of 1-2% D content, whereas those requiring an amorphous product may contain up to 20% D content.

Injection molding is the primary fabrication method for producing- PLA parts. PLA could be a semicrystalline polymer. The crystallinity and other physical properties of these materials can vary with the processing conditions.

Presence of certain additives such as nucleants[6], and accelerants, impact modifiers, and mold flow agents can affect the crystallinity and the properties as well. A drawback of PLA is its low Tₘ (approximately 60-75 °C) resulting in inferior thermal resistance to other industrial polymers. The thermal resistance can be improved by increasing the crystallinity in these materials. Higher crystallinity is also desirable for stiffness, strength, and other properties of the fabricated parts[6]. However, the crystallization rate of PLA is slow, thus obtaining sufficiently high crystallinity within reasonable manufacturing times is difficult. Even with optimum mold temperature settings (minimum of 85 °C, and preferably above 105 °C), the typical mold-closed time is in the 40–60 seconds range which is impractical for high volume production. The high mold temperature required also increases the cost of production. Lowering the cycle time and the prescribed mold temperature could lead to parts sticking to the mold, or bend and warp upon ejection. Subsequent annealing to increase the crystallinity of molded products is a viable strategy but would add an additional step (time and cost) to the overall manufacturing process.

The crystallization od PLA is of great interest to the research community and studies have focused on influences of axial stretching/strain[7], melt drawing/extrusion[8], annealing[9], and crystallization temperature[10] on PLA crystallization.

This research was focused on the effect of processing conditions on the crystallinity during vibration assisted injection molding.

3 RESULTS AND DISCUSSIONS

3.1 Experimental Technique

An Ingeo™ PLA 2500HP polymer from NatureWorks was utilized in this study. To enhance the properties of the final products, we added 10% proprietary blend of additives that included a nucleating agent, accelerant, impact modifier, and a mold flow agent. PLA pellets were dried in a 40°C oven for 8 hours to reduce the amount of absorbed moisture[11].

The samples were molded into ASTM D638-01 dog bone specimens using a Nessei PS40E5A injection molding machine. Injection molding was performed with and without vibration using the modified setup presented in figure 1. During the processing the melt was dynamically oscillated under 4 different conditions: i. without oscillation (0 Hz), ii. 1 Hz, iii. 4 Hz, iv. 8Hz, and v. 30Hz. Melt oscillation was commenced immediately as the melt was injected and packed into the cavity for the duration of 5 seconds. To ensure a positive pressure on the melt during
oscillation, a 55:45 ratio of time was set for the compression stage relative to the decompression stage of each vibration cycle.

The temperature of the material in the injection screw was controlled at 4 positions along the screw. The temperature at the nozzle, front, middle and rear sections of screw were maintained at 215°C, 205°C, 195°C and 175°C. Injection pressures in all cases are set at 64 and 36 MPa respectively for injection period and packing period. The injection time for each sample was 20 seconds while the packing/cooling time was 15 seconds. To enhance the growth of crystal, a high temperature mold of 85°C was used for manufacturing all samples.

A cross sectional slice at the mid-section of the dog bone sample, weighing approximately 8-10 mg, was extracted from each sample and was utilized to investigate the crystallinity in the parts. A differential scanning calorimetry (DSC) technique was utilized for this purpose. Only the first heating scan, at 10°C/min, was collected to obtain the effect that each processing setup had on the molded material. The degree of crystallinity ($X_c$) was calculated using Equation 1.

$$X_c = \frac{\Delta H_m - \Delta H_c}{\Phi_1} \times 100$$ (1)

Where $\Delta H_m$ is the melting enthalpy [J/g], $\Delta H_c$ is the cold crystallization enthalpy [J/g], and 93 J/g is the melting enthalpy of a PLA crystal of infinite size

### 3.2 Results

Table I illustrates the effect of vibration and cycle time on the product quality. The cycle time is the time required to produce a dog bone part. A minimum cycle time of 35 seconds was required for fabricating a high quality part without vibration. But with 1 Hz vibration, a cycle time of 21 seconds was adequate to get sufficient product. In contrast, dog bones fabricated without any vibration with 21 seconds cycle time were soft when demolded. There was no visible change in the product quality when the vibration frequency was increased to higher values.

A series of DSC tests were performed on the dog bone samples to gain insight on the crystallinity.

DSC scan profiles of injection molded samples processed under different conditions in the temperature region from 120°C to 190°C are presented in Figure 3. A DSC plot of the as received material has also been included.

Table II shows the percentage of crystallinity for each sample.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Crystallinity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unmolded Pellets</td>
<td>32</td>
</tr>
<tr>
<td>Conventional Molding</td>
<td>42</td>
</tr>
<tr>
<td>VAIM 1Hz</td>
<td>52</td>
</tr>
<tr>
<td>VAIM 4Hz</td>
<td>59</td>
</tr>
<tr>
<td>VAIM 8Hz</td>
<td>59</td>
</tr>
<tr>
<td>VAIM 30Hz</td>
<td>66</td>
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Samples under the same vibration frequency but with different cycle times were also tested to understand the effect of cycle time. Figures 4 and 5 show the DSC scan profiles of 1Hz VAIM samples and 30Hz VAIM samples, the degree of crystallization are presented in Table III.
2. Experiments show that the cycle time to manufacture a dog bone sample can be reduced from 35 seconds to 21 seconds using VAIM without inducing any negative impacts to overall product quality.

**REFERENCES**


