Vibration Assisted Injection Molding: An Innovative Energy Efficient Processing Technique for Poly-Lactic Acid (PLA) with Enhanced Properties

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ABSTRACT

This work is focused on the development of time and energy efficient injection molding processing strategies to fabricate semi-crystalline plastic components with enhanced properties. A Vibration Assisted Injection Molding (VAIM) process was devised for this purpose. This research was focused on understanding the effect of processing parameters such as vibrational frequency and cooling time on the mechanical and structural properties of semi-crystalline grade poly-lactic acid (PLA). It was observed that VAIM can reduce the cycle time for fabrication of PLA by 40% as compared to conventional injeciton molding. Furthermore, the VAIM samples had enhanced ultimate tensile strength, 50% more on average, even with the reduced cycle time as compared to the traditional injection molded samples. The VAIM samples had higher crystallinity and larger ratio crystalline domains of α phase than traditional injection molded samples. It was concluded the enhanced crystallinity was the primary contributor for enhanced properties and efficient fabrication.

Keywords: vibration assisted injection molding, PLA, crystallinity, production rate

1 INTRODUCTION

1.1 Vibration Assisted Injection Molding

A vibration assisted injection molding (VAIM) system has been developed and improved over the years by the current research group at Lehigh University [1, 2]. In this system the standard injection molding process is augmented with a dynamic oscillatory motion of the injection screw to induce a controlled elongational shear stress on the melt along the flow direction. In the latest iteration, the system controls vibration pressures, frequencies, amplitudes, and durations as the melt is packed and solidified. A schematic of the setup is illustrated in Figure 1.

In VAIM, during injection stage, the movement of the injection screw is controlled by an external computer system and moves forward and backward instead of moving forward only as in the case of traditional injection molding. The forward movement compresses the polymer melt and the backward movements decompresses the polymer melt. The frequency is controlled by the computer software. The amplitude is determined by compression and decompression time in one vibration cycle as well as the velocity of the injection screw.

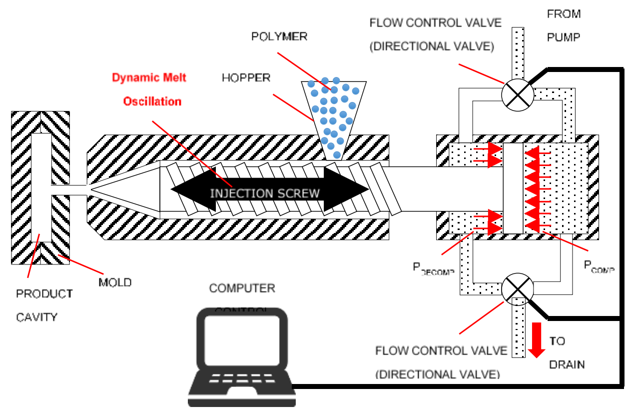

Figure 1: Schematic of Vibration Assisted Injection Molding System

1.2 Material Selection: PLA

The primary polymeric material of interest in this study is polylactic acid (PLA). The material is a polyester of lactic acid ($C_6H_6O_3$). PLA is a bio-based and biodegradable thermoplastic polymer derived from renewable resources, in contrast to common commercial grade thermoplastics derived from nonrenewable petroleum reserves. PLA is considered to be a favorable substitute to other polymeric materials for these reasons [3].

Injection molding is the primary fabrication method for PLA parts. Semi-crystalline PLA has a relatively slow crystallization rate as compared to other commodity polymers such as polyethylene (PE) and polyethylene terephthalate (PET) [4] and requires higher mold temperatures and longer cooling time [5], [6].

The crystallinity of PLA products can be enhanced by employing such methods as isothermal annealing, polymer blending and strain-induced crystallization. Isothermal annealing at temperatures in the range of 85-115°C for an extended period of time has been reported to initiate and develop the crystalline domains [7]. Addition of nucleating agents have been found to be effective in enhancing the growth of crystalline domains during fabrication [8–12].

In addition to formulation innovation, adding controlled shear rate during injection molding has shown to improve crystallinity and performances for many polymer materials including PLA. Such controlled shear rates have been imposed by dynamic manipulation of the polymer melt in the mold by either physical motion of the melt or by pressure modulation on the melt. The shear stress is expected to stretch the polymer molecules along this direction leading to alignment of the molecular chains. In semi-crystalline polymers, the alignment of the polymer chains provides favorable nucleation sites and augment crystallization during the cooling stage. The enhanced crystallization has been reported to be of shish-kebab morphology that extends well beyond the skin layers of the molded parts. The enhanced crystallization affects the mechanical properties favorably. Li et al. investigated the effect of vibration on ABS and PP fabrication during VAIM and observed that the mechanical strength of the parts fabricated from either material was enhanced with increased pressure amplitude or the vibrational frequency [13]. Angstadt et al observed that ABS samples fabricated with VAIM had higher degree of molecular orientation thus had improved tensile strength as compared to traditional injection molded samples [14].

In this research, the effect of vibration frequency on crystallinity, crystal structures and mechanical performances during vibration assisted injection molding of a commercial grade semi-crystalline PLA was investigated. The results were compared to those obtained from conventionally injection molded samples fabricated under identical conditions. Additional optimization of the processing conditions were performed as well.

2 EXPERIMENTAL APPROACH

2.1 Sample Preparation

An Ingeo PLA from NatureWorks was utilized in this study. This particular grade of PLA contains 90% PLA (2500HP) and 10% proprietary blend of additives such as nucleating agent, accelerant, impact modifier and mold flow agent to enhance the fabricability in extrusion and injection molding process. The as-received pellets were dried at 40°C for 8 hours in an oven to reduce the amount of absorbed moisture immediately before using them. Pellets were fabricated into Type I dog-bone confirmed to ASTM D638 standard using a Nissei 40-ton injection molding machine.

VAIM samples were named after the frequency of vibration while traditional injection molded samples were called CIM (conventionally injection molded) samples. The VAIM was performed at 4 different frequencies, (i) 1Hz, (ii) 4Hz, (iii) 8Hz, and (iv) 30Hz. The vibration was introduced to the polymer melt at the beginning of the injection stage and continued for 10 seconds. A 55:45 compression to decompression time ratio was utilized for each vibration cycle. The other processing parameters were controlled directly from the Nissei machine. The injection and packing time for each sample was 15 seconds while the cooling time was either 6 seconds or 20 seconds. A high temperature mold of 85°C was used for fabricating all samples to enhance crystallinity development.

2.2 Characterization Techniques

The crystallization behavior of PLA during processing utilizing VAIM is of primary focus in this research. A combination of two different techniques: Differential Scanning Calorimetry (DSC) and Wide-Angle X-ray Diffraction (XRD) was utilized to understand the effect of VAIM process on the crystallinity development in the samples. The phase transitions and the melting behavior of the samples were investigated utilizing a Q2000 DSC system from TA Instruments. A cross sectional slice at the mid-section of the sample, weighing approximately 8-10 mg, was extracted and tested in the DSC system. The sample tested in DSC include the surface layers, the intermediate layers, and the core of the PLA dog-bone specimen. Only the first heating scan performed at 10°C/minute from 25°C to 200°C was collected. The degree of crystallinity (X_C) was calculated using Equation (1).

$$Xc = \frac{\Delta H_m - \Delta H_c}{\Delta H_M} \times 100 \qquad (1)$$

where ΔH_m is the experimentally observed melting enthalpy [J/g], ΔH_c is the experimentally observed cold crystallization enthalpy [J/g], and ΔH_M is the latent heat of melting for the material of interest. It is 93 J/g for a PLA crystal of infinite size.

The crystallinity of the parts was characterized utilizing a PANalytical Empyrean XRD system (Bragg-Brentano geometry, Cu-Kα source, 1.54184Å, 40kV, 40mA). A step scan protocol with step size of 2θ = 0.01° and time per step = 120 seconds was used for the xrd studies. An area of 16mm × 10mm section at the center of each of the dog-bone samples fabricated under various conditions was scanned.

To validate the effect of VAIM on product properties, mechanical properties of the samples were characterized following the ASTM D638 standard. The stress-strain response was measured at room temperature (25°C) and atmospheric conditions (relative humidity of 50%) on an Instron 5567 mechanical testing instrument. The tensile testing was performed on all specimens using an initial load of 0.5±0.2 N and a constant crosshead speed of 5 mm/min.

3 RESULT AND DISCUSSIONS

3.1 Dimensional Stability

The effects of vibration and cycle time on the dimensional stability of the molded parts were studied right upon fabrication. It was observed that the minimum cycle time for traditional injection molded samples was 35 seconds (15 seconds injection time and 20 seconds cooling time) at 85°C mold temperature. VAIM samples on the other hand could be fabricated with a cycle time of 21 seconds (15 seconds injection time and 6 seconds cooling time) at the same mold temperature. A set of VAIM samples with a cycle time of 35 seconds was fabricated for comparison. Overall,

all samples fabricated in the study were opaque. The VAIM samples with 21 seconds and 35 seconds cycle time were observed to be defect free on visual inspection. The samples fabricated without vibration with 21 seconds cycle time were soft and the middle section was stuck to the fixed side of the mold when the mold was opened, resulting in deformed and unacceptable parts.

3.2 Crystallinity Development

The xrd plots for the samples fabricated with and without vibrations with 35- and 21-seconds cycle time are presented in Figure 2. The low intensity peaks are magnified for better identification in the inset. All samples fabricated were observed to be highly crystalized.

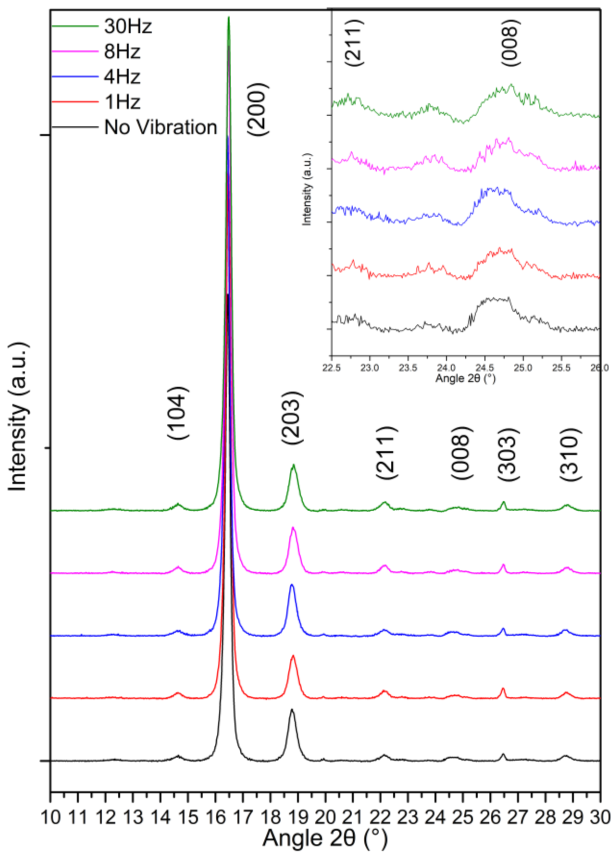

Figure 2: Xrd scan for 35 seconds samples

The (200) peak is centered at 2θ=16.62038° for α phase (JCPDS#00-064-1624) and 2θ=16.43569° for α´phase (JCPDS00-064-1623). The peak center for (203) is at 2θ=19.01994° for α phase and 2θ=18.71289° for α´ phase. It was observed that for the 35 second cycle time samples, the (200) peak center of both VAIM and CIM samples was at 2θ=16.46°±0.02°, while that for (203) peak was at 2θ=18.82°±0.02°. For the 21 seconds cycle time samples, the (200) peak center of both VAIM and conventional injection molded samples was at 2θ=16.46°±0.005°, while that for the (203) peak was at 2θ=18.83°±0.01°. The peaks from all the samples were centered very close to that of the α´ phase with slight shift towards higher angle (α phase). It was concluded that both α and α´ phases are present in the samples fabricated in both VAIM and traditional injection molded samples. An attempt to deconvolute the peaks for the α and α´ phases mathematically led to non-convergence to a unique solution. Since the peak locations are closer to α´ phase compared to α phase it was concluded that α´ is the primary phase. The α´ phase is known to be the primary phase injection molded PLA samples [15]. A set of higher resolution scans were performed in the range of 2θ=21-26° to validate the existence of α phase crystalline structures. It was observed that the intensity of α phase peaks (212, 213 and 300) increased as vibration frequency increased from CIM to 30Hz (Figure 3).

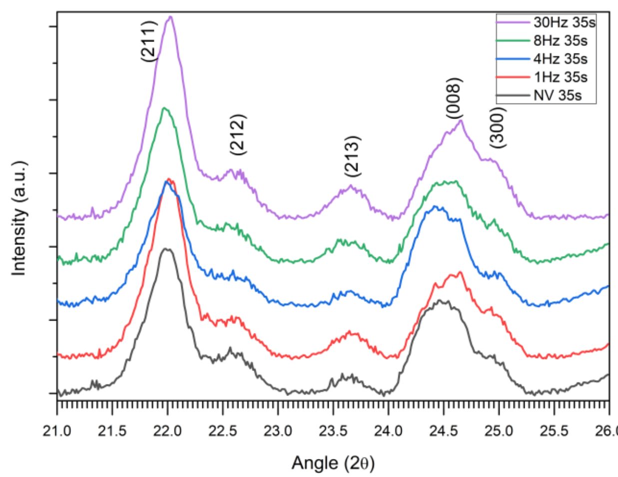

Figure 3: High resolution scan for 35 seconds samples

The degree of crystallinity for each sample as calculated from the area of the melting endotherm of the DSC curves is presented in Table I. It could be clearly seen that the degree of crystallinity of VAIM samples is higher than the ones fabricated with CIM process even with reduced cycle time.

Sample	Crystallinity (%)
Unmolded Pellets	32
CIM	42
VAIM 1Hz 35s	52
VAIM 1Hz 21s	54
VAIM 4Hz 35s	59
VAIM 8Hz 35s	59
VAIM 30Hz 35s	66
VAIM 30Hz 21s	60

Table I: Degree of crystallinity for CIM and VAIM samples

3.3 Mechanical Performances

The stress-strain curves of traditional injection molded samples and VAIM samples with 21 seconds cycle time are presented in and Figure 4. The ultimate tensile strength (UTS) for traditional injection molded part was 26.3 MPa with a standard deviation of 1.4 MPa while the average UTS of the VAIM samples was 39.8 MPa with the standard deviation of 4.1 MPa. The Young's modulus of the samples was similar, 1.40 ± 0.01 GPa irrespective of the fabrication conditions. The elongation at fracture was 2.6% - 4.6% irrespective of the fabrication conditions.

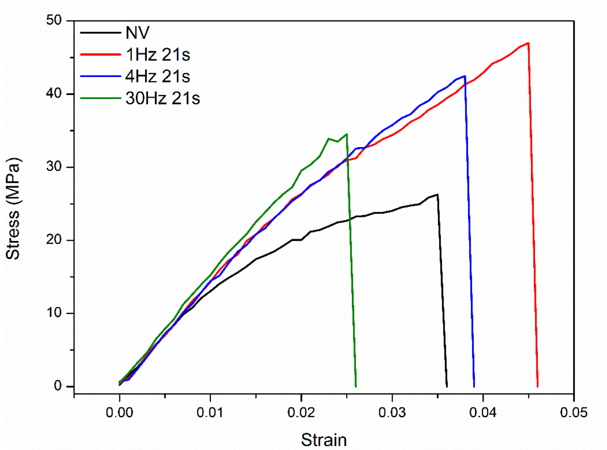

Figure 4: Stress strain curves for VAIM samples fabricated with 21 seconds cycle time

4 POTENTIAL IMPACT

Research showed that the cycle time can be reduced by 40% (from 35 seconds to 21 seconds) for commercial semi-crystalline PLA. To examine the financial feasibility of installing VAIM control systems to an injection molding unit, the cost per sample fabricated was compared between VAIM and CIM. The cost of one VAIM unit was estimated to be \$3118 without the cost of injection molding machine. The total cost included computer system, generic boards, I/O modules, LabVIEW software, ect. The annual maintenance cost was estimated to be 2% of the total cost of VAIM unit. Adding the VAIM system to a traditional injection molding machine increased the operation rate from \$ 213.74/h to \$ 289.62/h. But the hourly production rate increased from 103 samples/h to 171 samples/h. The total cost of each product was calculated as \$ 2.08 for CIM unit. In contrast, the cost of VAIM sample can be calculated as \$ 1.69 per sample.

The cost of each product reduced by 18.6% if VAIM was implemented. This case study considered small volume production. Normally, the lifecycle of a manufacturing facility is about 5-10 years and the production are in larger volume. That would reduce the cost of production further and provide a larger benefit.

5 CONCLUSION

The primary conclusions are as follows:

1. VAIM enhanced the crystallinity development in semi-crystalline PLA. 1Hz VAIM samples showed 52% crystallinity as compared to 42% for CIM samples. At 30Hz the crystallinity increased further to 66%.
2. The major phase formed in all fabricated samples was α′ phase for both CIM and VAIM samples. Increasing vibration frequency from 1Hz to 30Hz promoted the formation of the more stabled α phase crystalline structures.
3. The cycle time was reduced by 40% (35 seconds to 21 seconds) during VAIM as compared to CIM accompanied by the enhanced crystallinity development.
4. VAIM samples exhibited 50% higher UTS as compared to CIM samples (from 26.3MPa to 39.8MPa).
5. Implementing VAIM system can reduce the cost of fabrication by 18.6%. Larger volume fabrication and longer life-cycle could reduce the cost even more.

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