Assessing the Effect of Processing Variables on the Mechanical Response of Polysytrene Molded Using Vibration-Assisted Injection Molding Process

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Received 22 July 2003; accepted 21 March 2005
DOI 10.1002/app.22396
Published online 19 December 2005 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The present work is focused on the study of vibration-assisted injection molding (VAIM) process, using polystyrene as a model polymeric system. This recently developed polymer processing operation is based on the concept of using motion of the injection screw to apply mechanical vibration to polymer melt during the injection and packing stages of injection molding process, to control the polymer behavior at a molecular level, which would result in improvements/alterations to the mechanical behavior of molded products. In this study, the afore-mentioned concept was verified experimentally from monotonic tensile experiments and birefringence measurements of VAIM molded polystyrene in comparison with those of conventional injection molding process. The results of our study indicate that the actual degree of strength improvement depends on at least four parameters, namely, vibration frequency, vibration amplitude, vibration duration, and the delay time between the injection start and the vibration start. Furthermore, when these parameters were optimized, as much as a 28% strength improvement was observed, accompanied by an increase in toughness. Furthermore, birefringence measurements revealed that VAIM processing significantly altered the residual stress distribution throughout final products, but it did not, however, change the material density in the products. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 99: 2603–2613, 2006

Key words: injection molding; vibration-assisted injection molding; orientation; polystyrene; mechanical properties; melt manipulation

INTRODUCTION

One of the most common manufacturing techniques for polymeric products is injection molding (IM). The injection molding process is suitable for the mass-production of polymeric products for a variety of applications ranging from automotive to medical applications. In these challenging business arenas, achieving superior quality is one way to gain and maintain a strong competitive position.

With this problem in mind, the concept of vibration-assisted injection molding (VAIM) has been developed. The basic idea behind VAIM is to enable enhanced control over rheological behavior during processing, which in-term could facilitate in altering the mechanical response of molded components to the desired level.

In any molded polymer component, molecular orientation is the main factor that dictates the rheological behavior and, hence, the resulting mechanical response of molded polymer. In general, during injection molding process, shear stresses caused by the shearing action of the polymer melt with the stationary mold walls are higher near the mold walls and decreases toward the core, thereby, inducing orientation of the polymer macromolecules in the flow direction. This creates an uncontrolled anisotropic molecular structure distribution in final molded polymer component, which are often associated with poor mechanical and optical product characteristics.[1]

It should be pointed out that the cooling during injection molding is problematic even when orientation considerations are ignored. This is because the cooling is typically accomplished by conduction, which is not ideal because thermoplastics have high heat capacities and low thermal conductivities. This combination of properties leads to both longer cooling times and nonuniform temperature gradients during the cooling. Since the rate of cooling of polymers is related to the rate of shrinkage, nonuniform shrinkage often results. This leads to undesirable skin-core structures and dimensional nonuniformities, which results in the development of internal stresses.

Another problem related to injection molding is the occurrence of weldlines, which form where multiple polymer flow-fronts meet.[2–10] This is very common with today's geometrically complex parts. A weldline

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Contract grant sponsor: National Science Foundation Presidential Faculty Fellowship Program; contract grant number: DMI-9350209.

Journal of Applied Polymer Science, Vol. 99, 2603–2613 (2006)

in molded parts causes a drastic localized strength reduction for several reasons. First, weldlines introduce molecular orientations and unfavorable fiber orientations in the case of fiber-filled polymeric systems. The orientation of molecules and fibers are primarily affected by shear stresses generated during the material flow within the mold. Because of the fountain-flow effect, molecules and fibers in weldline regions end up oriented perpendicular to the flow direction. These are "frozen-in" before completely relaxing, and the result is a localized anisotropic and mechanically weak structure.[3–5,8] The second problem associated with weldlines is poor localized bonding resulting from insufficient entanglement of the molecular chains at the weld interface. Flow-fronts usually contain foreign substances, such as gases and moisture, which reduces good interfacial bonding and leads to the formation of V-notches, which serve as stress concentrators and crack initiators during the product lifetime.[2–4,7,8,11,12] Lastly, even without orientation or inclusion related problems, weldlines would be weaker regions, anyway, as with conventional cooling the flow-fronts that meet at these locations are at relatively low temperatures and do not possess sufficient heat energy for effective self-welding.[3–5]

Thus, the afore-mentioned problems not only reduce product quality, but also cause inconsistencies in the properties from cycle to cycle result, which can cause major losses in both the time and money associated with product manufacture.

To resolve or at least minimize the problems mentioned earlier, various forms of "melt manipulation" techniques have been developed. These melt manipulation techniques typically induce oscillatory motion of the polymer melt during processing, which could in-turn affect the evolution of the structure throughout the molded product. The most common techniques that fit in this category are SCORIM,[11,13–35] Push-Pull,[15,16,24,32,36,37] RHEOMOLDING,[15,16,24,38–50] Moving Boundary technique,[23,51–53] Injection-Spin process,[54–56] and Vibration-Assisted Injection Molding.

As stated previously, this relatively newly developed technique was based on the concept of introducing oscillatory energy to the polymer melt during injection molding processing. More specifically, a mechanical vibration was applied to the polymer melt during the injection and/or packing stages, in an effort to alter the rheological behavior of the polymer melt. It is well known that the rheological behavior of a polymer is dependent on the pressure, temperature, and shear rate distributions that are present during processing. In general, shear stresses induced during the injection stage tend to relax (diminish) during the packing stage. The material's temporal rheological behavior along with the rate of cooling affect molecular orientation and relaxation processes, which in essence determine the final molecular structure of the cooled molded polymer. The technique used in this study relies on the control of the pressure and strain histories of the polymer melt to alter the rheological characteristics of the molten polymer.

This article, one among a series of papers to be published, addresses the structure–property relationships during a VAIM process. In this study, a practical and deployable form of vibration assisted injection molding was utilized to elucidate the effects of specific molding parameters, namely, vibration frequency, vibration duration, vibration amplitude, vibration profile, and vibration starting time on the mechanical response of molded polymer, using polystyrene (PS) as a model material.

EXPERIMENTAL

In this study, to elucidate the effects of vibration assisted injection molding experimentally, a modified injection molding (IM) capability was developed that applies mechanical energy to polymer melts during molding, by oscillating the injection screw in a compression–decompression manner. This was accomplished by developing an open-loop hardware/software control system to actuate hydraulic valves appropriately and produce a forward–rearward motion of the injection screw. In this study, a Gateway 2000 GP6 series personal computer fitted with an analog/digital (National Instruments, CA) converter was used in conjunction with a LABVIEW –Version 5.0 (National Instruments, CA) software program, which enabled the user to specify a number of vibrational molding parameters. Two power relays were used to amplify the control output signals emitted by the DAQ board in an effort to assure that sufficient electrical power was provided to operate the hydraulic compression and decompression valves of the injection molding machine. The actual injection molding machine utilized during the present study was a BOY 15S (BOY Machines Inc, Lionville, PA), which has a screw diameter of 25 mm. In addition, a linear-variable-differential transducer (LVDT –RDP Group, Wolverhampton, United Kingdom) was installed onto the machine to monitor the screw position during the cycle. We note that the LVDT had the accuracy up to 0.1 mm. Furthermore, mold temperatures were controlled through the use of a Reglomat RT20 thermolater (Thermal Care Inc., IL) that supplied heated water in a closed-loop network of hoses to an ASTM standard (ASTM D638) "dog-bone" tensile test mold with two Kistler (Kistler Instruments Ltd., Amherst, NY) pressure transducer embedded in the cavity.

The experimental system was configured so that the VAIM controller would dictate the action of the machine hydraulic control valve during the injection and holding/packing stages of molding processes. Details of hydraulic actions to be taken are specified by the

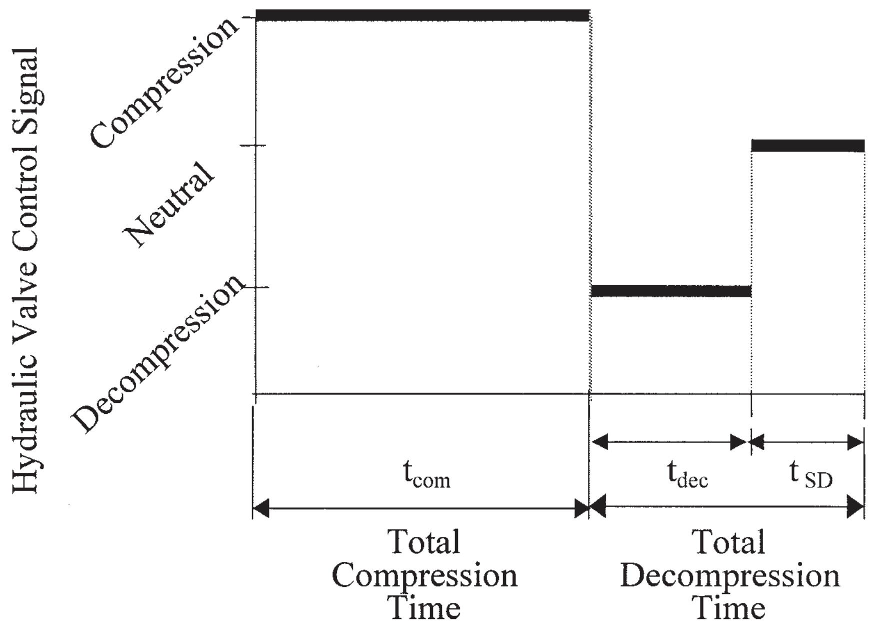

Figure 1 VAIM control signal sent to the hydraulic valve during a single vibration cycle.

user and were transferred on to the machine in the form of vibration control functions generated by the LABVIEW software. In an effort to supply oscillatory pressure vibrations to the polymer melt, the LABVIEW code simulates the manual operation of pushing and releasing the injection and decompression switches on the injection molding machine in an alternating fashion.

In this study, the effects of five molding parameters were investigated, namely, delay time to begin vibration (t_{del}), vibration duration (t_{dur}), vibration frequency (f), intracycle compression duration (t_{com}), and intracycle decompression duration (t_{dec}). The first three of these parameters are self-explanatory. The delay time to begin vibration was defined as the amount of time between the start of injection and the start of applied vibration, and the vibration duration was defined as the amount of time that the applied vibration continues once it was initiated.

As described earlier, the vibrational action was applied through the sequential compression and decompression of polymer melt by the axial forward and backward motion of the injection screw. The intracycle compression and decompression duration times (t_{com} and t_{dec}) correspond to the amounts of time that the valve was actually activated in each mode during each cycle. For practical purposes, a switchover delay time (t_{sd}) to be applied during transitions from decompression to compression was designed into the LABVIEW software code. The purpose of such a delay was to enable some degree of barrel screw stroke control and avoid too much backward travel during the decompression stage. During the delay period, the hydraulic valve was placed into a neutral state, and the injection screw remained in a stationary position until the next compression signal was provided. The actual level of the switchover delay time was automatically computed within LABVIEW program, using eq. (1) indicated later.

$$t_{sd} = \frac{1}{f} - t_{com} - t_{dec} \quad (1)$$

Thus, to enable such a switchover delay, the sum of the compression and decompression duration times specified by the user must always be less than the period of a vibration cycle. This can be seen in Figure 1, where the control signal sent to the hydraulic valve during a single vibration cycle is depicted.

It is to be noted that if one complete vibration cycle were to be explained in terms of time, the duty cycle would be represented by the ratio of the total time that the system was in a compression or forward motion mode to the total time that the system was in a decompression or backward motion mode. These total compression and decompression mode times are shown in Figure 1 for clarity. Thus, the duty cycle can be mathematically defined as

$$\mathrm{DC} = \frac{t_{com}}{t_{dec} + t_{sd}} \quad (2)$$

It is to be noted that duty cycle values of at least 1.0 was utilized, as permitting too much decompression was found to yield insufficiently packed final molded specimen.

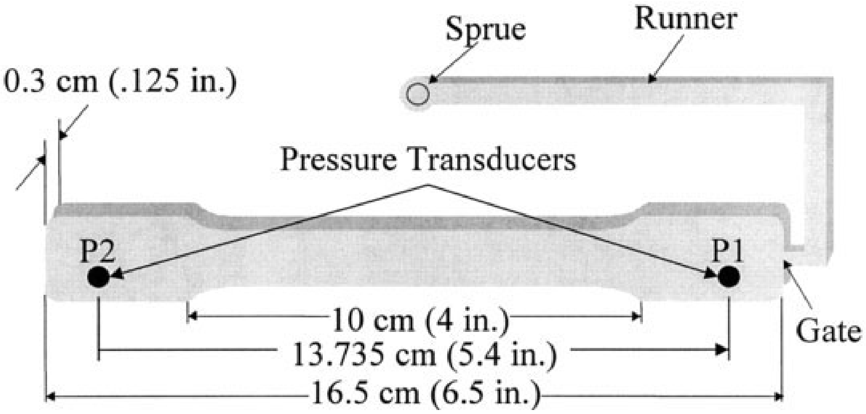

Figure 2 ASTM D638 type 1 specimen.

Materials and product selection

The material type utilized in the present study was polystyrene (STYRON 666DW produced by DOW Corp.). This material had an average molecular weight of ~230,000 g/mol and a MSDS reported tensile strength of 44.8 MPa.

Nominal measurements of the specimens along with the general sprue and runner configuration are provided in Figure 2. Two pressure transducers were installed in the mold cavity to monitor the pressure changes during the cycle due to the vibration energy applied by the injection screw. The locations of the pressure measurement locations are also shown in Figure 2. Furthermore, monotonic tensile strength measurements were made using a Phoenix mechanical testing machine (Measurement Technology Inc., Phoenix, AZ), using a crosshead speed of 5 mm/min at ambient temperature of 23°C.

Selected molding conditions

To effectively study the impact of VAIM processing, molding conditions that produced the strongest specimens without vibration-assistance were first determined. For the polystyrene used in this study, ranges of molding conditions centered upon those recommended by DOW were utilized. A large number of specimens were molded and tested, and through an optimization process a full set of conventional molding conditions that yielded the highest tensile strengths were determined. These conditions are presented in Table I. It is to be noted that throughout the remainder of the investigation, the processing conditions shown in Table I were applied, regardless of whether or not vibration assistance was utilized.

Range of vibration parameters studied

The hydraulic system of the BOY 15S molding machine utilized was capable of producing suitable injection screw oscillations at frequencies up to 9 Hz. Therefore, the frequency range studied during this present effort was from 1 to 8 Hz. The delay times to begin vibration ranged from 0.0 to 1.0 s, and vibration duration levels ranged from 4.0 to 12.0 s. Lastly, duty cycles between 1.0 and 3.0 were investigated.

Within the window of the parameter levels specified earlier, an experimental optimization process was carried out, focused on arriving at sets of VAIM processing conditions that would yield the highest tensile strength for the material studied. During this process, ~1700 sample specimens were molded and tested. The results that were generated are presented throughout the remainder of this article.

RESULTS AND DISCUSSION

First, as part of this investigation, 50 specimens were conventionally molded using the optimized processing conditions listed in Table I. The specimens were then tested monotonically, which revealed an average tensile strength of 45.2 MPa with a standard deviation of 1.68 MPa. This strength distribution was thereafter taken as the best that could be achieved through conventional molding, and was utilized as a baseline to compare strength variations with VAIM processing technique.

TABLE I
Optimized Molding Conditions Utilized Throughout the Investigation

Injection time	0.5 (s)
Holding time (s)	19.5 (s)
Cooling time (s)	15 (s)
Inecdon pressure	45 (MPa)
Holding pressure	45 (MPa)
Mold temperature	70 (°C)
Nozzle temperature (°C)	210 (°C)
Barrel temperature (front) (°C)	205 (°C)
Barrel temperature (rear) (°C)	200 (°C)

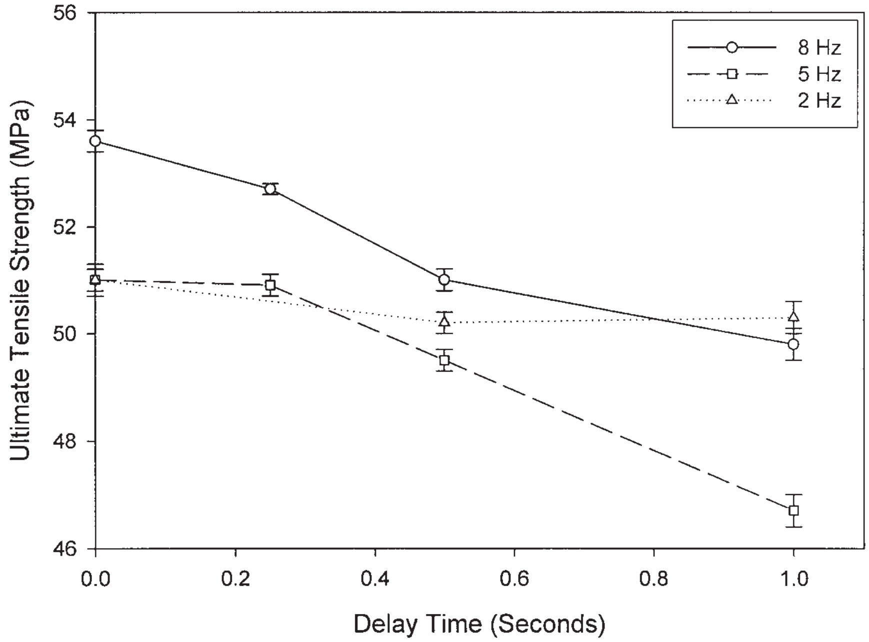

Figure 3 The effect of vibration delay time on ultimate tensile strength.

In an effort to uncover the related fundamental science-base, the optimization of product strength through VAIM processing was accomplished by first developing an understanding of the effects of individual vibration-related processing variables. For this purpose, the individual effects of critical parameters, namely, delay time before vibration application, vibration duration, duty cycle, screw vibration amplitude, and vibration frequency was investigated.

First, in the present study, a number of delay times were utilized, to best ascertain the optimal time to begin the application of the vibrational energy. These ranged from 0 s, corresponding to initiating the vibration simultaneously with the injection, to 1 s, which implied that the vibration was initiated after the actual mold cavity was filled. Figure 3 shows the plot of the effect of delay time on the ultimate tensile strength at three levels of vibrational frequencies, namely 8, 5, and 2 Hz. The results clearly indicate that initiating the vibration sooner rather than later clearly led to higher product tensile strength levels. While this was found to be true at all frequency levels, the dependence of tensile strength on delay time was found to be most critical at the higher frequency levels. For example, as indicated in Figure 3, the strength of specimens molded using a vibrational frequency of 2 Hz decreased only slightly as delay time was increased. But, as the applied frequency was increased further to 8 Hz, however, the strength decreased dramatically as the vibration was initiated progressively later. On the basis of these results, the authors conclude that in the case of polystyrene the vibration energy should be introduced during the injection phase of the molding operation.

As can be imagined, the vibration energy applied during injection, probably, affects the flow behavior of the molten polymer. The authors believe that this modified flow behavior "may" have two aspects significantly different from that present during conventional injection molding process. One is related to skin formation, and the other relating to the shearing action between the mold wall and the molten polymer. It is known that polymer flow behavior, which is basically controlled by induced localized pressure and temperature, plays an important role in determining the formation and subsequent growth of the skin. During conventional injection molding, a thin skin is instantaneously formed at the point of contact between the molten polymer and the metal mold wall, where a relatively uniform pressure gradient exists. This uniform pressure gradient also induces a relatively uniform degree of shearing action between the molten polymer and the mold wall. When VAIM processing is utilized, however, the authors believe that the resultant pressure gradient is nonuniform and oscillates in concert with the applied energy, which in-turn could completely alter the dynamics of skin formation and growth, and as a result the final molecular structure throughout the molded polymer. During the present study, the modification of skin formation and growth induced by the earlier application of the vibrational energy obviously led to final morphological states associated with increased strength in the axial product direction.

Secondly, Figure 4 shows the variation of ultimate tensile strength of VAIM "dog-bone" specimens as a function of vibration duration ranging between 8 and 12 s. While several vibration frequency levels are cov-

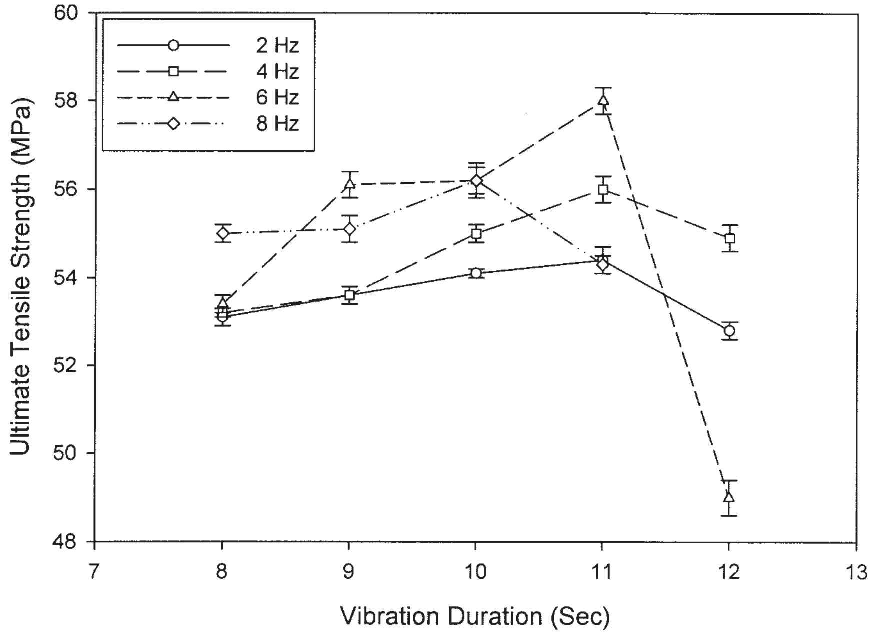

Figure 4 The dependence of ultimate tensile strength on vibration duration.

ered in Figure 4, the data included is otherwise limited to constant values of all of the remaining vibration-related parameters (i.e., the delay time to begin the vibration was 0 s for all of the data shown in Fig. 4). From Figure 4, we observe in general that when the duration of the applied vibrational energy was varied in the range between 4 and 12 s, it was uniformly found that the strongest specimens resulted when duration times on the order of 10 or 11 s were applied. As can be seen, tensile strength levels of 54.4, 56.8, and 58.0 MPa were obtained when the optimal vibration duration level of 11 s was applied with frequencies of 2, 4, and 6 Hz., respectively. For the higher frequency of 8 Hz, it was found that a slightly lower duration time of 10 s was actually better, which yielded an ultimate tensile strength of 56.3 MPa.

Thus, the results of the experiments clearly indicate the profound importance of the vibration-duration. In general, the results observed appears to indicate that the oscillatory energy needs to be applied long enough to enable appropriate structural orientation, but not so long as to continue to disrupt the orientation once a critical polymer solidification condition was achieved. Thus, for polystyrene investigated in this study, this critical material state was apparently achieved at around 10 s after the injection started.

Thirdly, while a duty cycle range of 1.0–3.0 was investigated during the present study, it was found that not all duty cycles could be applied at all frequencies. During VAIM processing, forces are imposed on the injection screw by both the hydraulic system on one end and the molten polymer on the other end. Depending on the injection and decompression speed settings on the machine, only certain ranges of duty cycle were actually found to be obtainable at given vibration frequency levels. For the speed settings utilized during the present study with polystyrene as a model material, duty cycles less than 1.0 were found to yield a net backward motion of the screw. This condition produced situations in which the packing pressure that could be applied to the molten polymer was insufficient. On the other hand, duty cycle values that are too large were also found to yield undesirable results; as such conditions did not allow sufficient screw movement during decompression phases. As the vibration frequency was increased, it was found that upper limits on duty cycle exist at which almost no oscillation of the injection screw results. The actual levels of these upper duty cycle limits were found to decrease as frequency was increased.

The overall finding with regard to duty cycle during the present investigation is that a level of 1.0 appears to be optimal. This is shown in Figure 5, where average product strength levels for two duty cycle levels at three different vibration frequencies are presented. From Figure 5, it can be clearly seen that the "1 to 1" duty cycle leads to tensile strengths that were significantly higher compared with those obtained with a duty cycle of 1.5 at all frequency levels. When larger duty cycle levels were applied, it was consistently found that the ultimate tensile strength continued to decrease. The authors believe that this is due to the fact that the polymer tends to be more continuously manipulated or excited by the vibration energy when the duty cycle was set to a level of 1.0. For larger duty cycle levels, the polymer has more time to effectively

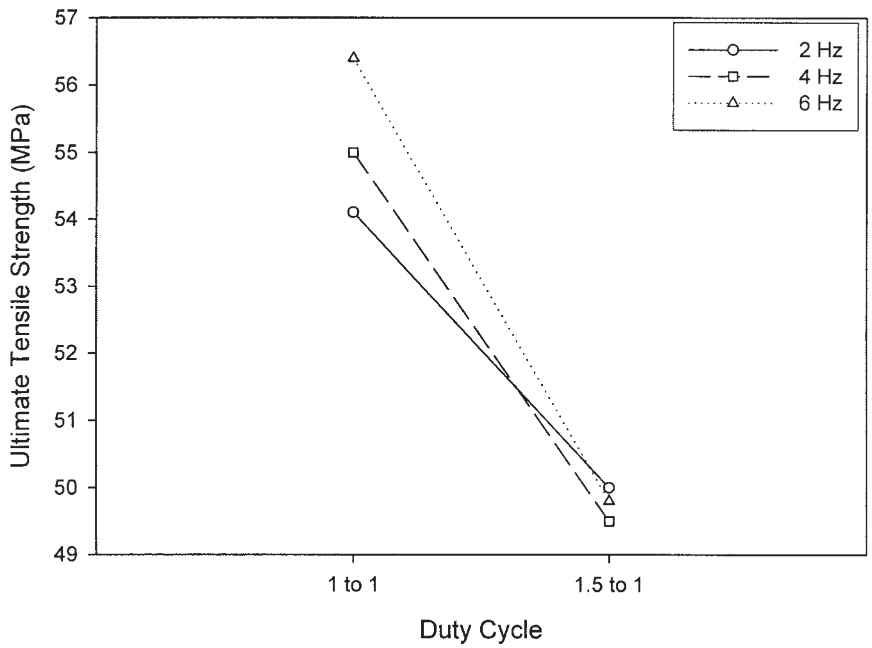

Figure 5 Effect of vibration duty cycle on resultant product ultimate tensile strength.

relax during the portion of the compression phase not accompanied by screw motion. For example, in the current study, for a frequency of 1 Hz and a duty cycle of 2–1, 0.66 s of each 1 s cycle are spent with the screw in a compression mode. Of this, only about 0.3 s was utilized for actual forward screw travel, with the remaining compression time being equivalent to static packing during conventional molding. During static packing, a polymer is subjected to high pressure, but still can start to relax any orientation effects that were imparted during flow. Thus, if too much static compression or packing is included during each cycle of VAIM, the melt manipulation effects imparted by the vibration could be partially lost. Thus, minimized duty cycle levels, which at the same time do not allow a net retraction of the screw to occur, appears to be optimal. In many ways, the effects of duty cycle appear to be very closely related to those of actual screw oscillation amplitude, which are discussed in the next section.

To study the effects of screw vibration amplitude on tensile strength, three amplitude levels were tested at three different vibration frequencies. This was accomplished by adjusting the duration of time that the screw was in the active decompression mode during each vibration cycle. Referring back to Figure 1 and eq. (2), this could be done without altering the duty cycle by adjusting the relative sizes of the active decompression and switchover delay times. For each frequency studied, the highest amplitude level was that which resulted for the selected duty cycle and the smallest switchover delay time that produced stable vibration cycles without a net screw retraction. Once this was determined, medium and low levels of amplitude were obtained by modifying the decompression and switchover delay times, while maintaining the duty cycle at the selected level. For each frequency, medium and low levels of screw vibration amplitudes were those that were ~75 and 50%, respectively, of the corresponding maximum screw amplitude obtainable (i.e., the high amplitude level).

As was done for all of the previously discussed vibration related parameters, the investigation into the effects of screw amplitude involved testing with a wide variety of combinations of the other parameters. Figure 6 shows the plot of variation of ultimate tensile strength as a function of screw oscillation amplitude at three levels of vibration frequencies. From Figure 6, we observe that in all cases the large amplitude provided superior tensile strength over the medium and small vibration amplitudes. The authors believe that an explanation for this type of phenomenon is very similar to that which was previously provided in relation to duty cycle. If the injection screw rests in a stationary position too long during the decompression phase, the polymer tends to relax. When this occurs, once again the orientation effects that are imparted by the active melt manipulation could be partially lost, leading to a weaker final molecular orientation in the axial direction. Thus, it appears that maximizing the screw stroke amplitude not only provided the maximum amount of melt manipulation within the mold cavity to induce orientation, but also minimizes the nonactive portion of each cycle, during which detrimental polymer relaxation could occur. Optimal VAIM processes during the present study, therefore,

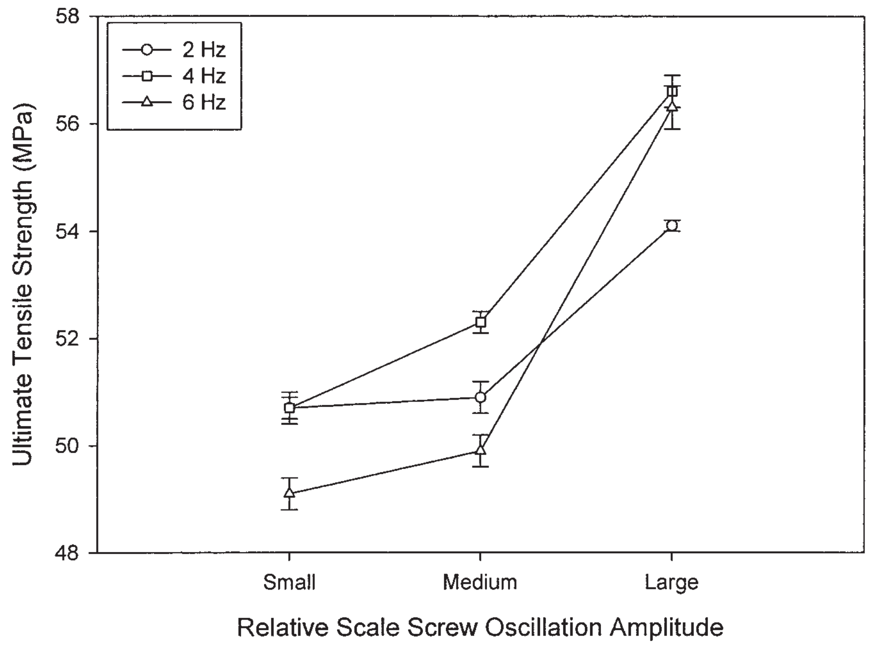

Figure 6 Effect of screw vibration amplitude on product ultimate tensile strength.

were those that imposed maximized screw stroke amplitudes with for the most part continuous melt manipulation during each oscillation cycle.

The presentation of the effects of vibration frequency will be accomplished by taking into account all of the previously discussed optimal vibration-related parameters and comparing the characteristics of the strongest samples that resulted at each frequency. This is illustrated in Figure 7, where the ultimate tensile strength distributions of specimens molded with otherwise optimized VAIM processing conditions for four vibration frequencies. The curves shown are for vibration frequencies of 2, 4, 6, and 8 Hz, with the duty cycle of 1.0, and maximized screw stroke amplitude. Also, an optimal vibration duration level of 10 (8 Hz) or 11 s (2, 4, and 6 Hz) was utilized. Furthermore, each distribution curve was obtained using 30 samples, and in essence represents the best that could be accomplished during the present study at that particular frequency. For comparison purposes, a corresponding strength distribution curve obtained from a sample of 30 products optimally molded

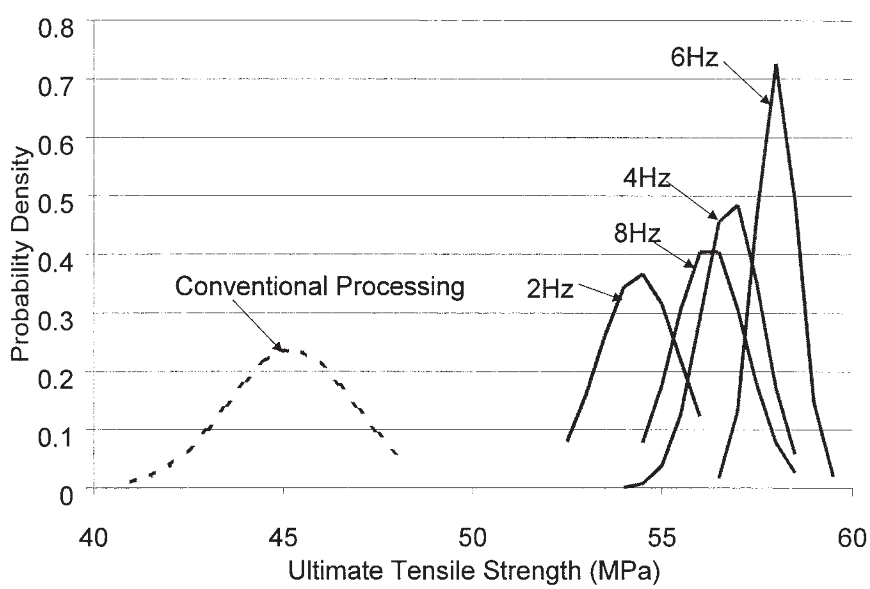

Figure 7 Statistical comparison of VAIM and conventional processing 1.

TABLE II
The Enhancement of Product Strength Through VAIM Processing

Processing technique	Average UTS (MPa)	Strength improvement (%)	SD (MPa)	SD reduction (%)
Conventional Molding	45.2	—	1.68	—
Optimized VAIM (Hz)				
2	54.4	20.4	1.08	35.7
4	56.8	25.7	0.81	51.8
6	58.0	28.3	0.54	67.9
8	56.3	24.6	0.95	43.4

through conventional processing is also included in Figure 7. As can be seen from the Figure 7, optimized VAIM processing yielded molded polystyrene that were far stronger than those obtained through conventional molding, at all frequencies. The actual levels of the improvements over conventional processing realized are presented in Table II, where quantitative strength increases and sample standard deviation reductions are listed. As can be seen, optimized VAIM processing at 6 Hz yielded the overall best products, with a 28.3% strength improvement and 67.9% sample variation reduction relative to conventional processing.

As far as the product strength dependence on vibration frequency is concerned, the average ultimate tensile strength increased with frequency up to a threshold frequency level of 6 Hz. As shown in Figure 7, however, optimized VAIM processing at 8 Hz was not as good as that at 4 or 6 Hz. This finding could be explained if one assumes that the effectiveness of VAIM is related to the locally imposed strain and associated energy within the product cavity. The actual maximum levels of screw stroke amplitude that were obtainable during the present study for the 2, 4, 6, and 8 Hz VAIM processing represented in Figure 7 were 20.9, 7.1, 3.0, and 2.1 mm, respectively. While from a net melt manipulation standpoint increasing frequency compensated for the decrease in imposed stroke up to 6 Hz; at the 8 Hz vibration frequency, the extremely small stroke amplitude apparently limited the orientation energy locally provided throughout the mold cavity.

In addition to comparing the ultimate tensile strength of the molded polystyrene specimens, it is interesting to compare actual stress–strain curves. Figure 8 shows the representative tensile testing curves for conventional molding and VAIM molding at 4 and 6 Hz vibration frequencies. As is evident from Figure 8, VAIM processing not only improved the ultimate tensile strength, but also increased the strain to failure and overall product toughness, which is the area under the stress–strain curve.

Finally, while the investigation of the material changes associated with VAIM is likely to be the subject of a number of studies in the future, it was felt that including a short discussion of such changes in the current work would be useful. In an attempt to provide insight in this area, the optical birefringence, which is an indicator of residual stress levels in molded specimens are presented for both conventionally molded and VAIM processed molded specimens

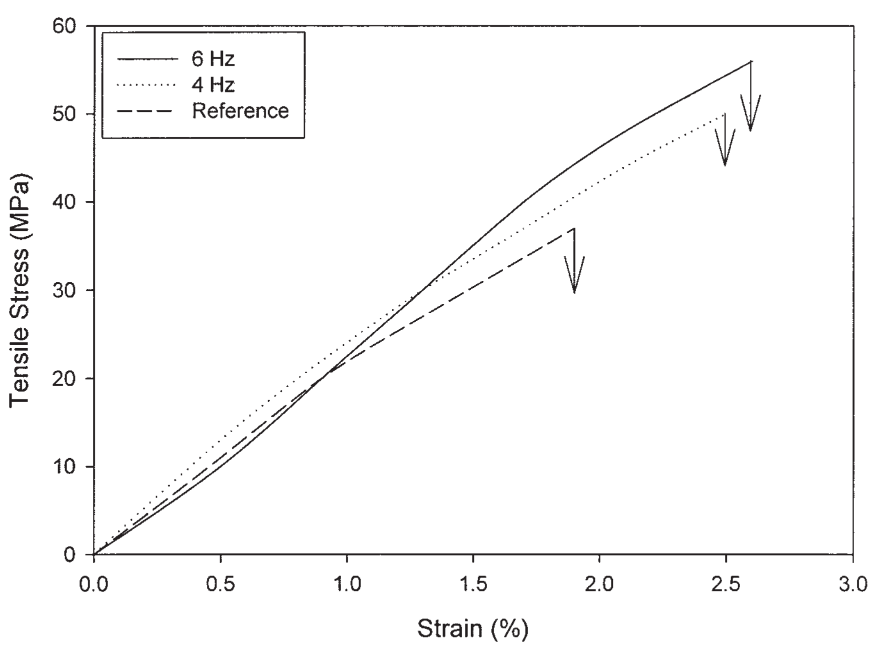

Figure 8 The improvement of product toughness through VAIM 2.

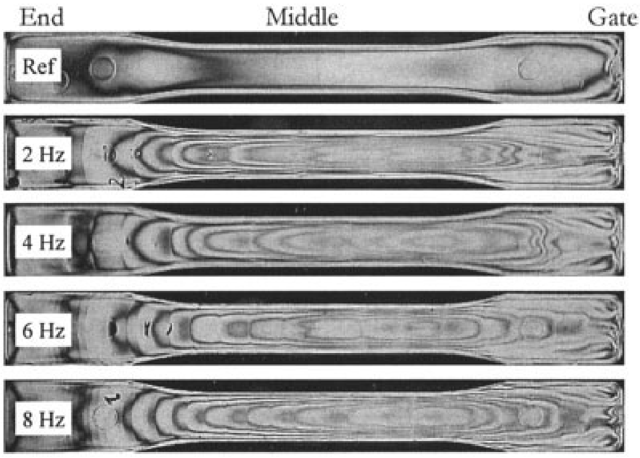

Figure 9 Comparison of birefringence patterns for conventional and VAIM processed products.

(Fig. 9). As can be seen from Figure 9, the birefringence pattern measurements were made through the thickness of the test specimens. First, the birefringence observed in the middle section of the control sample indicated as "Ref" in Figure 9 shows a very nonuniform pattern. On the other hand, the birefringence patterns observed with samples molded using VAIM processing are much more uniform, which indicates that VAIM processing changed the residual stresses within final parts. It can also be seen from Figure 9 that for the VAIM samples, the residual stresses are more uniformly distributed within the parts at the middle section. However, the residual stresses in conventionally molded parts were found to have large variations. This observation supports the fact that the residual stresses play a primary role in determining the mechanical properties of molded polymer components.

Unique birefringence patterns can also be observed in the end sections of VAIM processed parts. As can be seen from Figure 9, the birefringence patterns in these areas appear as repeating "flow front-like" patterns. The authors believe that these repeating patterns were probably formed during injection phase of the polymer processing operation. Furthermore, the length scale of this "flow front-like" repetitive pattern obviously varied with applied vibration frequency. As can be seen, VAIM processing is approximately twice that for 4 Hz, three times that for 6 Hz, and four times that for 8 Hz. This makes sense if one considers the actual decompression times associated with each of the processes, which when compared yield identical ratio levels. Since the vibration was applied during injection phase, it can be expected that the distance between two repeating "flow front-like" patterns multiplied by the cross-sectional area of the part is approximately equivalent to the volume that could be compressed and decompressed within a given vibration cycle.

Another material characteristic that was examined was density. The densities of the parts discussed earlier were measured and compared with the control sample as shown in Table III. The results shown in the table were obtained from the average of 10 samples. As can be seen, the difference in the densities between conventionally molded and VAIM processed samples are negligible, and hence one could conclude that the strength improvement through the use of the VAIM processing is not due to an increase in density. Hence, the strength improvement has to be due to other factors, such as induced orientation effects.

CONCLUSIONS

While the development of a detailed understanding of vibration-assisted injection molding processing is still in its infancy, the present investigation served to uncover a number of key issues associated with this relatively new technique. First, as found during the study VAIM processing can significantly strengthen molded polymer samples and at the same time markedly improve product uniformity from cycle to cycle. The actual degree of strength improvement depends on at least four parameters; which are vibration frequency, vibration amplitude, vibration duration, and the delay time between the injection start and the vibration start. When these parameters were optimized for polystyrene, as much as a 28% strength improvement with an associated product standard deviation reduction of over 67% resulted. The toughness of the products manufactured was also increased through VAIM processing, and all of these results were obtained without making major machine modifications or increasing the processing cycle time.

Finally, when the product birefringence was studied, it was found that VAIM processing does significantly alter the residual stress distribution throughout final products. It does not, however, change the material density in the products. While much remains to be learned about vibration-assisted injection molding, the technique has been shown to be very promising as a means for potentially dramatic manufacturing improvements in the future.

TABLE III
Comparison of Density for Conventional and VAIM-Processed Products

	Density (g/cm^3)	Difference (%)
Conventional	1.036	—
Optimized VAIM (Hz)		
2	1.027	−0.87
4	1.034	−0.19
6	1.037	0.09
8	1.037	0.09

Materials and equipment utilized during the present study were graciously provided by Mark Barger of DOW Chemical Corp. and Peter Santiago of TherMold Partners Inc. In addition, the guidance and support provided by other members of the associated industrial advisory board, including Dr. Hamdi Demirci of Tyco Electronics, Todd Glogovsky and Lori Stuzik of Montell Corp., Mark Elsass of Ferromatik Milacron Corp., William Livingston of Polystyrene Recycling Company of America, and Dr. David Ardayfio of Daimler Chrysler is greatly appreciated.

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