Variables Strength Stress Bead Analysis in a Twin Screw Extruder

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Variables Strength Stress Bead Analysis in a Twin Screw Extruder

William Pappas, Harry Brown II, Graeme Fukuda, Roba Adnew and David Bigio,
University of Maryland, College Park, MD

Abstract

An experiment has been created that relates stress distribution history with residence time distribution. To quantify the results, stress beads that break up at a specific stress were used to measure the percent of material that sees those critical stress values throughout the extruder. Two different strength stress beads were used along with two different screw geometries at the mixing section to complete the experiment. This paper describes results for a range of different throughputs and speeds in the extruder.

Introduction

Extrusion is a viable technique for creating an array of different products across a broad spectrum of disciplines. Examples include pipes and tubes, chemical pressure-sensitive adhesives, and active ingredient patches for pharmaceutical industries [1]. One of the more intriguing applications for extrusion is the production of composite materials using fillers, such as carbon nanofibers. This process produces an extruded material with altered properties than that of the base polymer, such as heightened thermo-conductive and mechanical strength properties. There are several factors that determine the change in properties of an extruded material. One such factor is the amount of mixing a material within an extruder experiences. To be able to determine the degree of mixing, it is important that one accurately models the stress that is induced for a given screw geometry and operating condition.

Mixing with a twin-screw extruder is categorized as either distributive or dispersive. Distributive mixing uniformly distributes particles throughout the melt and dispersive mixing breaks large particles and distributes them throughout the melt. Narrow kneading blocks are used for distributive mixing as the melt flows in and around the paddles, producing low shear. Dispersive, however, is a high shear process as it utilizes wide kneading blocks. Wide kneading blocks force the material around the blocks that is squeezed between the paddles and the barrel wall [2].

There have been numerous attempts in the past to find a correlation between stress in an extruder and a residence-time distribution. Efforts have been made to use the residence distribution to imply intensity of mixing by various methods, e.g.; Peclet number or a number of passes [3]. Typical residence distributions, however, only provide an axial history of the flow and give no information regarding the stress history. In a recent study, it was shown that for any given operating condition there was a higher percentage of stress beads that saw the critical stress for wide kneading blocks compared to narrow kneading blocks. It was also revealed that the amount of stress increases as specific throughput and screw speed increased [8].

The aim for this paper is to explore in greater depth what accounts for these breakup differentials in wide and narrow kneading block residence stress distributions (RSD). Two different batches of stress beads were utilized to aid in the insight to this question. The two different critical stresses at which these beads break up in give a larger range of data, allowing to further pin-point where the true damage is occurring in the extruder. Operating conditions were the same for all experiments so the comparison is strictly due to geometry.

Materials

The extrusion material used for this experiment was high-density polyethylene (HDPE) Alathon H6018 in pellet form from Equistar Chemicals. The HDPE had a density of 0.960 g/cc and a melt index of 18.0 g/10 min.

Stress sensitive sensor beads were utilized as the method to measure the stress in the extruder. The beads are used to measure shear stress during mixing by breaking at specific critical stress levels which are dependent on the bead diameter. When the beads are subjected to stress levels beyond the critical shear stress, the beads break and release their encapsulated dye which stains the polymer melt. Two levels of stress beads were selected to determine if the individual bead could distinguish between the stresses induced by the different mixing elements. The critical stresses of the two beads used in this experiment were 92 kPa and 119 kPa.

Using the same dye that is encapsulated by the stress beads, Red B Disazo for the 119 kPa stress level beads and Automate Blue 8A for the 92 kPa, “reference” dye shots were produced. These shots were prepared by dissolving polystyrene pellets in xylene, and adding concentrated amounts of dye. The solution was allowed to solidify over a 24 hour period. The batch was then cut into small pieces and weighed to the amount of the measured stress bead shots. The dye shots were used to produce reference RTD curves that represented 100% breakup of the stress beads.

Equipment

The experiments were performed using a 28-mm Coperion CoTSE extruder with an L/D = 32 using two screw configurations of interest. The melting section of both screw designs remained unchanged for the duration of the experiment and consisted of one right-handed kneading block (28-mm) and one left-handed kneading block (14- mm). The mixing section of the first screw design contained two right-handed kneading blocks (15 and 42- mm) and one left-handed conveying element (28-mm). The second screw configuration consisted of four righthanded kneading blocks (15-mm) and one left-handed conveying element (28-mm). The extruder set up consists of a feed port and one vent port just before the mixing section, as seen in Figure 1. The extruded polymer was cooled via a chill roller where it was then collected as strips.

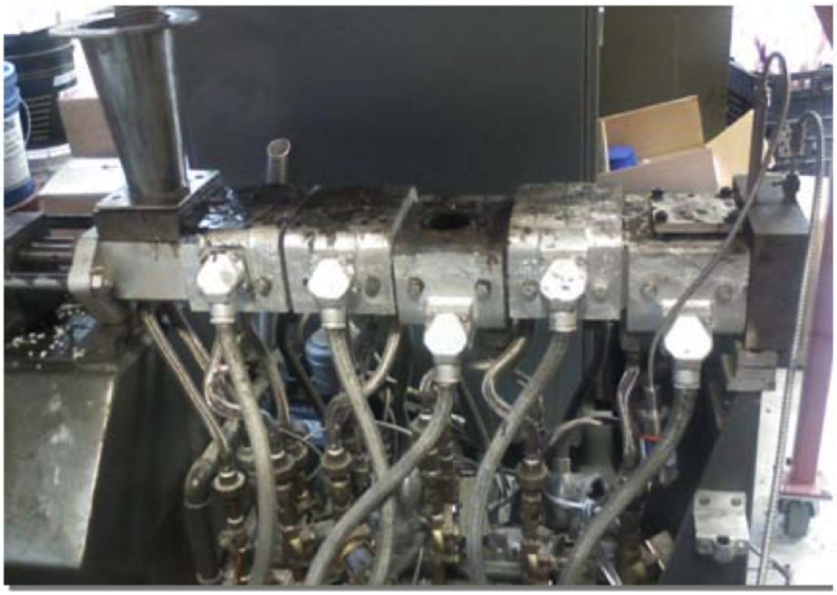

Figure 1. 28-mm Coperion Co-Rotating TSE

A reflective optical probe was placed just before the die of the extruder. The probe consists of a split fiberoptic bundle, where light was emitted from one of the fiber bundles. The light reflected off the polymer and screw elements, and was collected by the other fiber bundle, where it was converted into a voltage signal.

Experiment

The extruder and pellet feeder were set to the desired operating condition. The five barrels were set to a temperature of 200^{o}C and the die was set to 195^{o}C. The data acquisition program began sampling for 15 seconds to establish a baseline. Due to the transparent nature of HDPE during extrusion, TiO_2 pellets were fed at a constant rate during the experiment to provide a white background to the polymer melt so the optical probe could make measurements. Both the stress beads and the solid pieces of dye were injected into the vent port through a modified syringe. The tip was removed and covered tightly with a layer of thin lens paper. Then either the pieces of dye or stress beads were loaded into the syringe so that they lay on top of the lens paper. Adding a plastic point to the rubber tip allowed the plunger to pierce the lens paper releasing the shot. When the TiO_2 white baseline became constant the syringe would be held over the vent port and the shot would be injected in a single impulse. This method proved more precise in minimizing the channels the shot would disperse in. Since small amounts of the dye shots were fed into the extruder, the concentration of the dye and polystyrene had a negligible effect on the viscosity of the HDPE melt. Once the stained polymer had been completely extruded, the data acquisition program was reset and the program was again run for 15 seconds to establish a baseline. In total, nine operating conditions were tested, with two dye and two stress bead shots fed per condition.

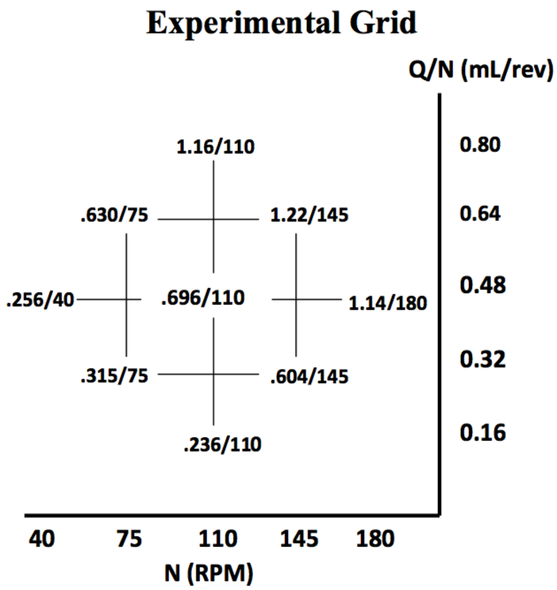

Figure 2. CCD grid of experimental conditions

A central composite design (CCD) of experiment grid was used to layout the data to show relationships between percent breakup and different operating conditions, as seen in Figure 2. This approach was chosen because of the expected non-linear relationship between breakup and the chosen parameters. The specific locations on the grid represent the operating conditions for this study.

The ranges of the conditions were determined by the capabilities of the extruder. The first number of a condition represents the throughput, Q, measured in mL/s. The second number represents the screw speed, N, in rpm. N vs. Q/N was chosen because RTDs scale with Q and N.

Theory

To better understand what mechanisms are responsible for breaking the beads, both shear and elongation (extensional) stress calculations were preformed. The shear stress was calculated using the following equation:

$$\tau = \mu \gamma^{n} \qquad (1)$$

Where τ is shear stress (Pa), μ is viscosity of the polymer (Pa-s), y is shear rate (1/s), and n is the power law index. The shear rate is defined as:

$$\dot{\gamma} = \frac{\pi N D}{h} \qquad (2)$$

where N is screw speed (rpm), D is the screw diameter (mm), and h is the channel height (mm).

The extensional equation is derived by considering a flow between two plates. One of the plates is stationary, and the other is moving towards the plate, as seen in the following figure below (Figure 3).

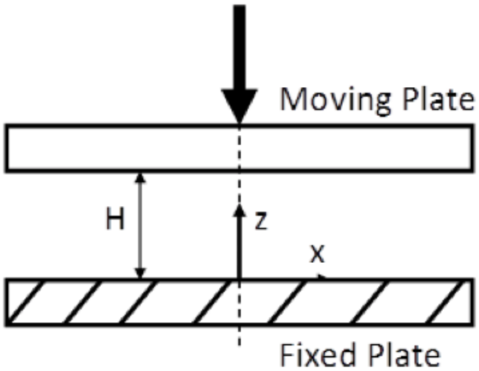

Figure 3. Squeezing plate figure

Starting with the vorticity equation and substituting in the stream function equation to solve for the stream function (which is done so in almost every fluid mechanics text book), the resulting equation is given by:

$$\psi = Vx\left(3\left(\frac{z}{H}\right)^2 - 2\left(\frac{z}{H}\right)^3\right) \qquad (3)$$

From Equation (3), the horizontal velocity component (u) can be obtained by:

$$u = \frac{\partial\psi}{\partial z} = Vx\left(6\frac{z}{H^2} - 6\frac{z^2}{H^3}\right) \qquad (4)$$

The term of interest is the extensional shear rate in the horizontal direction. To obtain this, Equation (4) is differentiated with respect to x.

$$\frac{\partial u}{\partial x} = \frac{6V}{H^2}\left(z - \frac{z^2}{H}\right) \qquad (5)$$

Integrating the z term over the height between the two plates, and adding scale terms to keep the dimensions of the equations the same, Equation (6) is derived.

$$\frac{\partial u}{\partial x} = \frac{6Vw}{H^3}\int_{z_o}^{z_f}\left(z - \frac{z^2}{H}\right)dz \qquad (6)$$

Where V is the velocity of the moving plate (mm/s), H is the final height between the plates (mm), w is the width of the kneading block paddle (mm).

The extensional stress (τ_e) can be calculated using Equation (7).

$$\tau_e = 3\mu\frac{\partial u}{\partial x} \qquad (7)$$

The results from both calculations are displayed in Table 1.

Screw Speed (N)	Shear Stress (kPa)	Extensional Stress: Narrow KBs (kPa)	Extensional Stress: Wide KBs (kPa)
40	8.0	42.6	136.2
75	14.4	76.5	244.8
110	20.2	107.1	342.6
145	25.5	135.5	433.4
180	30.5	162.1	518.4

Table 1. Calculated shear and extensional stresses

The extensional stress equation is a good approximation of the stress since it increases as the width of the kneading block paddle increases. Breakup in the kneading blocks could either occur in the flow in the channel or through the gaps between paddles. This would induce shear stress. Another possibility could be due to the squeezing of the fluid when opposing paddles approach one another. This causes elongational stress. Comparing the calculations, it is clear that the elongational stress has a higher magnitude than the shear stress approximations. This could provide some insight into the mechanisms that is causing the bead breakup.

Experimental Results

Percent Breakup

The average percent breakup for all nine experimental conditions was calculated and the results inserted into the Central Composite Design grid for analysis as a way to compare the breakup history in the wide and narrow kneading block configurations. To determine the percent breakup of stress beads, the areas under the RTD and RSD curves were calculated and used in the followed equation:

$$Percent\ Breakup = \frac{A_c}{A_r} x100\% \qquad (8)$$

Where Ac is the area under the RSD curve and Ar is the area under the dye RTD curve.

The first set of beads used in the experiment was the higher critical stress beads (119 kPa). Figures 4 and 5 below displays the percent breakup of stress beads in the CCD grid using Screw 1 and Screw 2, respectively.

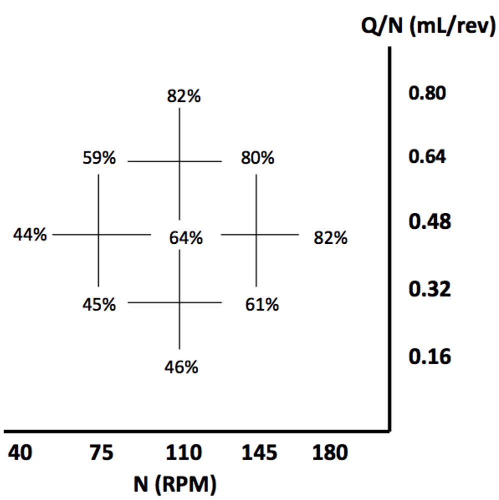

Figure 4. Percent breakup of 119 kPa beads using wide kneading blocks

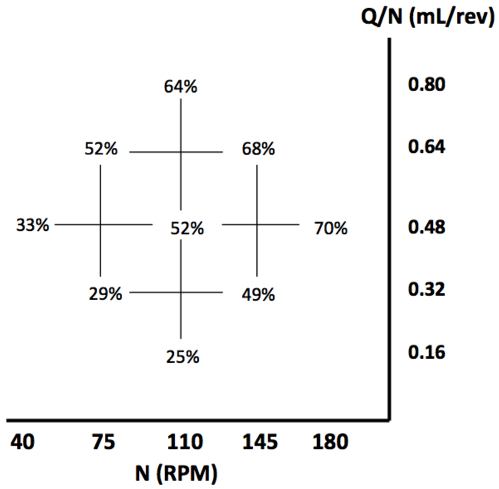

Figure 5. Percent breakup of 119 kPa beads using narrow kneading blocks

The CCD grids displayed in Figures 4 and 5 indicate that there are trends in the data that are consistent between the two screw geometries. As screw speed is increased for a given specific throughput, the percent breakup of the stress beads also increases. Additionally, as specific throughput increased, the percentage of broken beads also increased for a given screw speed.

Given the experimental error, which was calculated to be 2%, the average range of breakup for both grids is approximately 35% between the lowest and highest magnitude of breakup. However, differences between the grids exist. The magnitude of the percent breakups is different between the two geometries. The wide kneading blocks reach a maximum value of 82%, while the narrow kneading blocks only reach a maximum percent breakup value of 70%. Similarly, for a given operating condition, the percent breakup due to the wide kneading blocks is larger than the narrow kneading blocks, in every case. Through the trends in the data, screw geometry and screw speed are not enough to predict the amount of bead breakup that will occur. A consideration for the specific throughput also needs to be accounted for when predicting breakup.

The second set of stress beads (92 kPa) were then used, and the results of the experiments using wide kneading blocks were plotted in Figure 6 and the results using narrow kneading blocks were plotted in Figure 7.

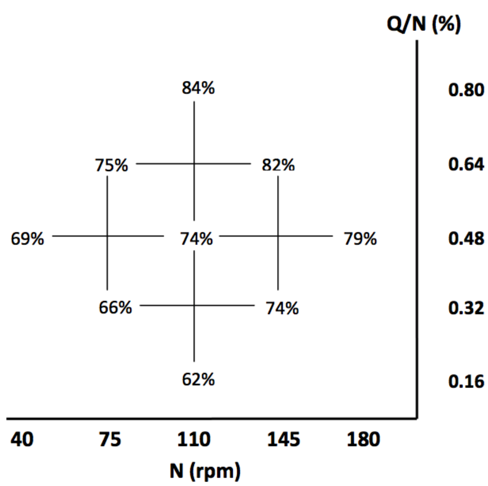

Figure 6. Percent breakup of 92 kPa beads using wide kneading blocks

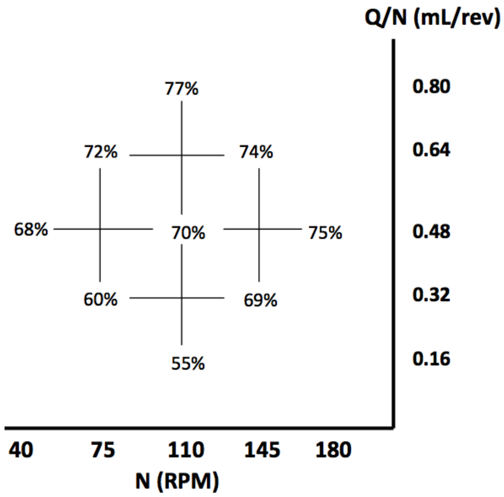

Figure 7. Percent breakup of 92 kPa beads using narrow kneading blocks

Similar to the plots shown in Figure 3 and 4, there are also consistent trends in the results of the experiments using the 92 kPa stress beads. It is seen again that by increasing Q/N and N, a higher percentage of stress beads that break is produced.

The average range of breakup for this set of geometries is approximately 15% between the lowest and highest breakup. The maximum breakup for the wide kneading blocks was found to be 84% and a maximum value of 77% for the narrow kneading blocks. Similar to the other results using the 119 kPa beads, the wide kneading blocks caused more beads to break for each operating condition in the experimental grid.

Looking at the two CCD grids for the 119 kPa beads and the two grids for the 92 kPa stress beads, there are similar trends between the two. For both sets of beads, as screw speed and flow rate are increased, the percentage of broken stress beads increased in every condition. Additionally, wide kneading blocks caused more breakup than narrow kneading blocks for each condition for both levels of stress beads. This again confirms the fact that wide kneading blocks are ideal for dispersive mixing because of the larger induced extensional flow.

Comparing the differences between the two sets of stress beads (Figures 3 and 4 versus Figures 5 and 6), it is apparent that there was less breakup using the stress beads that had a critical stress of 119 kPa than the beads with a critical stress of 92 kPa. This is most noticeable for the three operating conditions with the lowest flow rates (.256mL/s - 40 rpm, .315mL/s - 75rpm, and .236mL/s - 110rpm) where the average difference between breakups of the wide kneading blocks was approximately 20% between 119 kPa and 92 kPa stress beads, and even more apparent using the narrow kneading blocks where the average difference between the two stress beads is over 30%. However, the differences in percent breakup for the three operating conditions with the highest flow rates (1.16mL/s – 110rpm, 1.22mL/s – 145rpm, and 1.14mL/s – 180rpm) are not as large. The average difference for the narrow kneading blocks is a little more than 5% and there appears to be no difference for the wide kneading block geometry. This is due to the limitations of the analytical method, which can be seen in the residence stress distribution curves.

Residence Stress Distributions

Using the RTD and RSD curves generated by the experiments, a visual representation of the percent breakup could be generated, as seen in Figure 8.

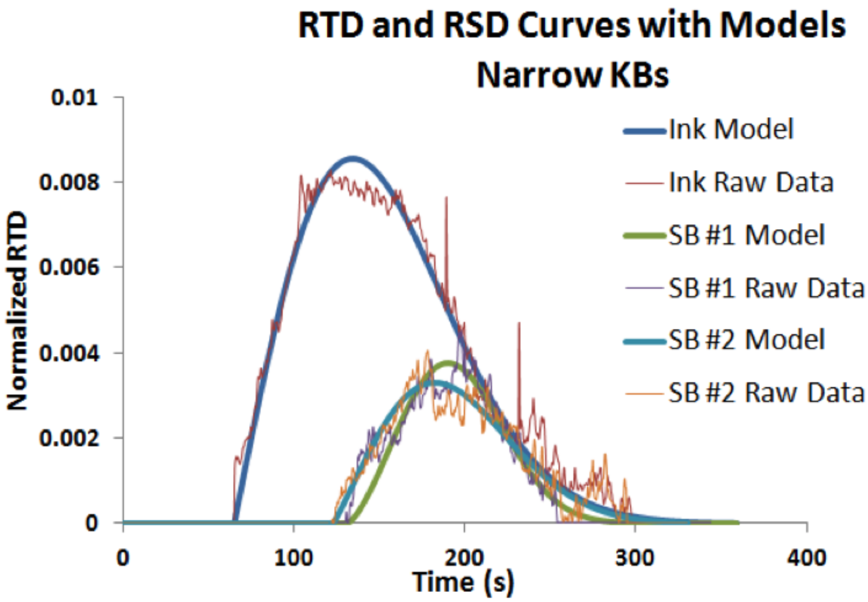

Figure 8. Normalized narrow kneading blocks RTD and RSD curves for .315mL/75rpm condition

The figure above shows the normalized RTD and RSD curves produced by the ink and 119 kPa stress beads (SB) shots, as well as models generated using a Weibull model. The percent breakup for this particular operating condition was 29%. The two sensor bead shots are nearly identical, indicating that the experiment is repeatable. Additionally, the amplitude of the ink curve is much larger than the sensor bead curves, indicating that 100% breakup was not achieved. It is clear that there is a delay between the start of the ink curve and the start of the sensor bead curves. As a percentage of the beads flow through the center of the channels in between the paddles of the kneading blocks, the beads experience very little shear stress. This delay time provides evidence that 100% breakup of sensor beads will never be achieved, and could indicate why more than 80% breakup could not be achieved for the 92 kPa stress breads using wide kneading blocks.

Conclusions

A previous paper has introduced the use of stress sensitive beads as an effective tool to measure the stress history in the complex geometries found in twin-screw extruders. For this experiment a comparison of wide and narrow kneading block screw configurations was performed over a range of specific throughputs (Q/N) and screw speeds (N) as well as over two different strength stress beads. For a given operating condition the percentage of beads broken was higher for wide kneading blocks when compared to narrows, of equal length, and for the 92 kPa beads when compared to the 119 kPa beads, of equal amounts.

These results can be interpreted in two ways. They first help to reaffirm that for the wide kneading blocks a higher percentage of stress beads experienced the critical stress at the same operating conditions, in all cases. This outcome has been replicated twice for each operating condition because this pattern holds true for both sets of beads. Secondly the results help to validate the use of the stress beads by showing that the beads do not break arbitrarily, but at certain predetermined critical stress values.

Through the calculation of shear and extensional stresses through the kneading blocks, it can be concluded that extensional stresses play a dominate role as the mechanism that causes the stress beads to break. This indicates that the stresses occur in the region between the two screws when the material on one paddle is forced to flow to either side of the paddle and is squeezed by the paddle from the other screw.

These results illustrate the validity of this method of modeling stress in a twin-screw extruder. Further analysis and experiments can yield even more insights into the stress history of an extruder. Such that it may be possible to dictate how much material sees certain levels of stress by selecting a screw geometry, specific throughput and screw speed.

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