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Combinatorial effects of kneading elements on twin-screw compounding

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An inline residence-stress-distribution methodology enables characterization of the effect of unique screw geometries on dispersive mixing.

One of the biggest advantages provided by twin-screw extrusion is the high degree of customization that it affords for screw design. Screws are composed of individual screw elements that together make up one screw configuration.[1] Among the multitude of different elements used, kneading blocks—one of the most commonly employed mixing elements—are made up of stacked discs or paddles of varying thickness that are staggered at an offset angle.

To determine the effect of paddle thickness on the mixing process, we studied two types of kneading blocks. These are made up of discs with either wide or narrow thickness stacked at 45° (the standard stacking angle for double-flighted twin-screw extruders). The wide discs are approximately three times the thickness of the narrow kneading blocks (4.8 vs. 1.6mm). In twin-screw compounding, base polymers are mixed with additives and fillers to introduce material properties that enhance their performance for specific applications. Efficient mixing, which can be decomposed into two parts—distributive and dispersive mixing—is crucial for maximizing these enhancements. Distributive mixing, a function of strain, controls the spread of the minor phase throughout the polymer matrix.[2] Dispersive mixing, on the other hand, is a function of stress, and breaks down agglomerates that form due to cohesive forces.[3,4]

We have developed an inline methodology that enables the characterization of residence stress distribution (RSD), thereby making it possible to measure dispersive-mixing efficiency.[5–7] Our methodology is centered on polymeric stress beads that rupture and release an encapsulated dye at a specified critical stress, which is determined by wall thickness and particle size. Using this encapsulated dye, we are able to measure a residence time distribution (RTD) representing 100% bead breakup. An estimate of the percent rupture (percentage of

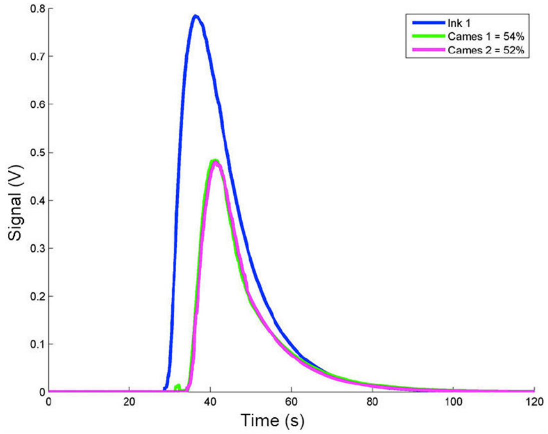

Figure 1. *Example residence time distribution (RTD) and residence stress distribution (RSD) curves. V: Voltage amplitude collected by the optical sensor. The blue curve represents the RTD. The green and pink curves represent two RSDs collected at the same operating conditions.*

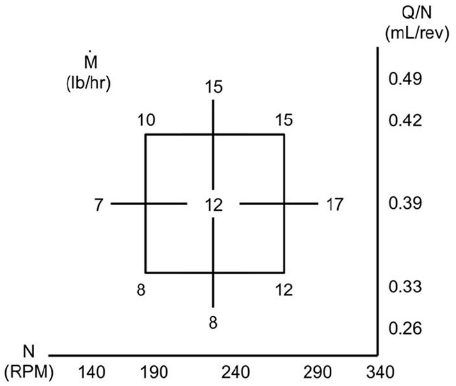

Figure 2. *Central composite design (CCD) grid showing mass flow rates. Q/N: Specific throughput. N: Screw speed.*

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Table 1. *Predictive equations for 48mm narrow and wide geometries.*

Screw geometry	Intercept	Screw speed (*N*)	Specific throughput (Q/*N*)	Geometry factor	R^2
Narrow 48	65.49	2.83	2.67	–	0.92
Wide 48	75.56	4.33	3.17	–	0.99
Combined	70.5	3.58	2.92	−4.94 (Narrow 48)	0.96

Table 2. *Predictive equations for 24mm narrow and wide geometries.*

Screw geometry	Intercept	Screw speed (*N*)	Specific throughput (Q/*N*)	Geometry factor	R^2
Narrow 24	37.11	3.42	1.42	–	0.96
Wide 24	41.78	3.08	2.25	–	0.96
Combined	39.5	3.25	1.75	−2.72 (Narrow 24)	0.96 0.96

Table 3. *Predictive equation for narrow-wide 48 geometry.*

Screw geometry	Intercept	Screw speed (*N*)	Specific throughput (Q/*N*)	Geometry factor	R^2
Narrow-Wide 48	66.44	2.42	2.92	–	0.99

broken stress beads) can be determined by dividing the area underneath the RSD curve by the area underneath the RTD curve: see Figure 1.

Using a design of experiment approach, we employed a central composite design (CCD) grid to gain statistical insight into the percent rupture rate of the polymeric stress beads (see Figure 2). In addition, the CCD grid allows for the creation of a predictive equation for the rupture rate as a function of significant operating parameters on a 95% confidence interval. The general form of the predictive equation can be seen in Equation 1.

$$\text{Percent breakup} = C + A \cdot N + B \cdot \frac{Q}{N} \qquad (1)$$

where C is the intercept (offset of percent breakup), A is the sensitivity associated with the screw speed, N is the screw speed in RPM, B is the sensitivity associated with specific throughput, and Q is the mass flow rate. The percent breakup is a function of only two parameters (screw speed and specific throughput), which determine the axes on our CCD grids. It should be noted that the N and the Q/N variables in the equation do not refer to the conditions of the tests, but rather the coordinates on the CCD grid.

We compared screw configurations that use a certain mixing section length (made up of 24mm kneading blocks) with a second configuration that had double the mixing section length (48mm). Furthermore, we made a second comparison between hybrid geometries (those with both wide and narrow kneading blocks) to study the effect that the ordering has on the dispersive mixing performance. The percent rupture rate data for the narrow-screw configurations with mixing-section lengths of 48 and 24mm can be seen in Figure 3(a) and (b), respectively. Figure 3(c) shows the rate for the narrow-wide hybrid geometry, in which the narrow kneading blocks are upstream of the wide kneading blocks. For more detailed pictures of the screw configurations, please see Figure 4.

Certain trends can be observed in all of the CCD grids. Analysis of Figure 3(a) and (b) shows that the 48mm mixing section causes the breakage of a greater percentage of stress beads than the 24mm section, with 1.7 times greater efficacy overall. Subsequent increases to the length result in a linear relationship between mixing-section length and percentage breakup. Tables 1–3 show the predictive equation

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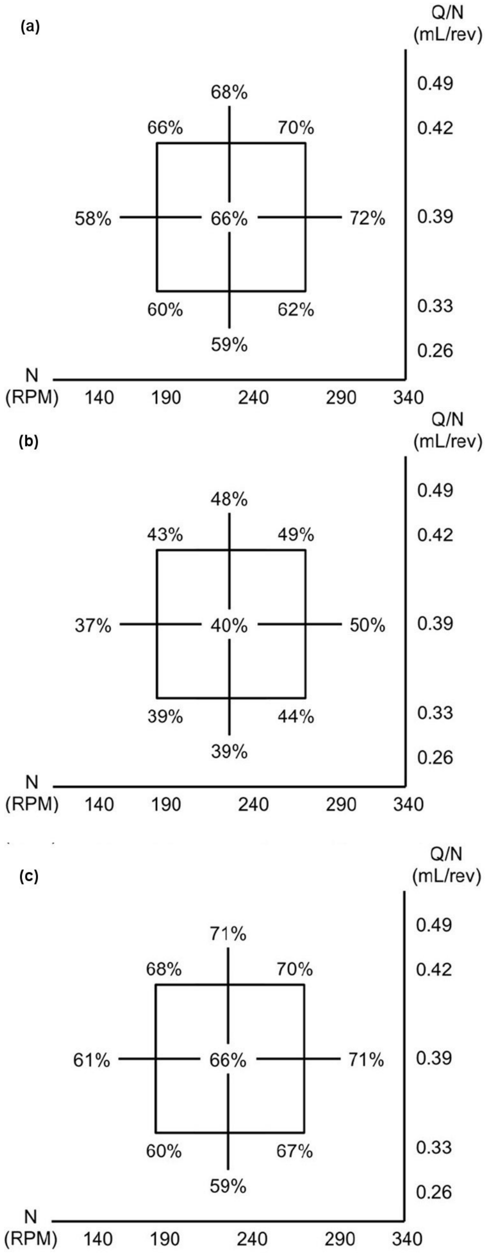

Figure 3. *CCD grid illustrating the percent breakup caused by (a) the narrow 48mm mixing section, (b) the narrow 24mm mixing section, and (c) the narrow-wide 48mm mixing section.*

results for all CCD grids that we tested. These equations corroborate the near-linear trend that occurs in the CCD grids when the mixing-section length is doubled, as is shown by the increase in the intercept value. Lastly, the narrow-wide geometry shows a greater similarity to the narrow-48mm configuration than to the wide-48mm mixing section. Although research from the RSD perspective on these hybrid geometries is only just beginning, our results indicate that the permutation of the kneading blocks represents a configuration change capable of causing significant differences in dispersive mixing.

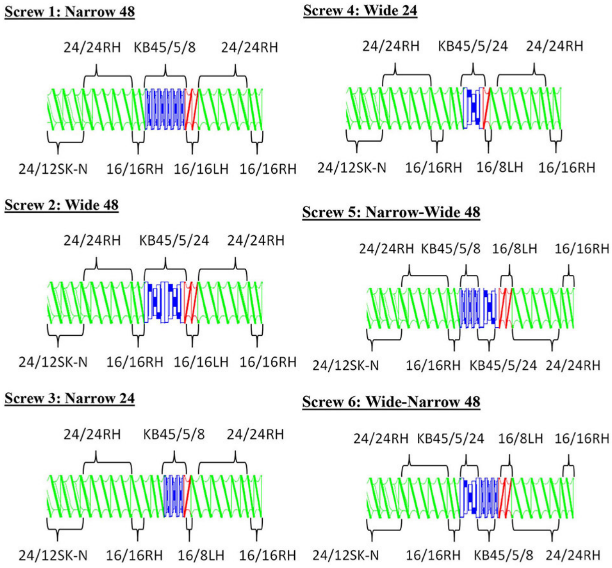

Figure 4. *Screw configurations. The green sections are forward-conveying elements, labeled by their pitch/axial length. The red elements are reverse-conveying elements. The blue elements are kneading blocks (KB), labeled with the stagger angle, number of paddles in an element, and the total axial length. RH: Right-hand (forward) conveying. LH: Left-hand (reverse) conveying. SK-N: Conveying elements with deeper channels to accommodate feed regions.*

The RSD inline methodology that we have developed represents a reliable technique for characterizing the dispersive-mixing performance of screw geometry. In addition to comparing screw geometries, this methodology also analyzes operating conditions at a quantitative statistical level. In future work, we will look to explore more complex geometries, scalability, and material properties.

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Graeme Fukuda has been involved in plastics research since 2011 and has been manager of the polymer processing laboratory since 2012. He earned the Lew Erwin Scholarship in 2012 and graduated with an MSc (with a focus on thermal fluids) in 2014.

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David Bigio, who received his PhD from MIT, has been engaged in the field of polymer processing for over 26 years, with a focus on mixing phenomena in extruders and injection-molding machines. He established the polymer processing laboratory, which is engaged in research dedicated to the quantification of mixing as a basis for extruder performance evaluation, and has been a member of the SPE Extrusion board since 1992. He has been Education Chair, ANTEC TPC, and ultimately Division Chair. Some of the accomplishments that occurred in those roles include: the creation of the MINITECS; the creation of the Lew Erwin Scholarship fund, to acknowledge and support undergraduate and graduate students in the field of polymer processing; and the initiation of the first Division awards in the area of twin-screw extrusion. He is currently the chair of the TOPCON committee.

Ben Dryer is a mechanical engineering graduate student. His research centers on mixing performance in the twin-screw extrusion process, with a specific focus on quantifying mixing performance to improve the scaleup of extrusion processes and to better predict material properties of a twin-screw compounded extrudate.

Jake Webb is an undergraduate student and performs research at the advanced manufacturing lab. His work involves using a clear-barrel twin-screw extruder to correlate the visually observed mixing of colored dye to the experimentally measured quantification of mixing.

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Paul Andersen, the director of process technology, is responsible for process engineering and new technology development for twin-screw compounding. He is a Past President of SPE and served on the Executive Committee from 2004 to 2011. Additionally, he has been an active member of the SPE Extrusion Division Board of Directors since 1990. He has authored many ANTEC and TOPCON technical papers, served as technical consultant for the SPE twin-screw extrusion educational video, and has written a chapter on twin-screw extrusion for the SPE Plastics Technician's Toolbox.

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Mark Wetzel is a research fellow in DuPont's central research organization, providing technical leadership in the area of polymer process development, scaleup, and analysis. He has over 35 years of experience in various areas and interacts with DuPont businesses, customers, and alliance partners. He has expertise in extrusion fundamentals, new materials synthesis through process innovation, and nanotechnology. He is an active member of SPE and its Extrusion Division and has served as an SPE Fellow (2008) and the Extrusion Division Chair (2010). He is now Councilor for the Extrusion Division.

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