Melting and Mixing Capability Enhancement: Technology Revealed

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Abstract: An extruder is a vessel for continuous processing of polymer and other materials where fusion of all ingredients can occur that may be accompanied by a chemical reaction or volatile extraction. The various ingredients in the material are forced to interact closely while undergoing size reduction (dispersion) to create a homogeneous mass as a result of weak adhesive bonds. The interaction of the materials in different states needs the presence of at least one polymer material that becomes the wetting medium or the matrix. Generally, the wetting medium is not present in a viscous state at the time of commencement of the process and therefore primary fusion of the matrix has to occur preceding the mixing or homogenization process. The kind of work that can be carried out inside the extrusion apparatus involves application of forces that causes shearing or smearing, elongation, bending, torsion and compression, a cocktail of forces that have a general term called kneading applied to it. In a co-rotating twin-screw extrusions system that is setup to deliver the right kind and amount of work (as a result of application of the right forces) at the right place (in the various extruder processing zones) for the right amount of time (resulting in a narrow residence time distribution considering all the molecules in a given volume), the progress of material through the extruder is generally highly controlled and such a system can be used to conduct sophisticated chemical reactions apart from the afore mentioned physical process to prepare materials with unique properties.

Origin of Co-rotating Twin-Screw Extrusion: By the middle of the 20th century, extrusion equipment based on a single screw was well established in rubber applications and in the process industries such as soap and brick making. Certain specialized devices such as Banbury mixers were also available for specialized mixing of viscous materials. However, the need for a device that can continuously process a chemical reaction that results in increase of molecular weight or viscosity without gelling spurred the development of newer extrusion technology that would later change plastics compounding forever. The early co-rotating twin-screw extruder was conceived as a reactor vessel where control was needed in the positive movement of the molecules with the possibility of mixing or stirring action. Roberto Colombo (1938) of LMP, Turing developed the first commercial co-rotating twin-screw and sold it to I.G. Farben. This design was licensed to manufacturers in France (now Clextral), England (R. H. Windsor) and Japan (Ikegai). Bayer-werk of I.G. Farben formed the High Viscosity group to develop further the extrusion technology for reactive extrusion. Booy (1978) provides the details of the work by Erdmenger (1954) who was assigned the task of engineering the co-rotating extrusion technology which was one of the three extrusion concepts that the high viscosity group led by Meskat pursued. Counter-rotating twin-screw extrusion developed by Kiesskalt and reciprocating single screw devices called Co-kneaders developed by List were the other two competing technologies. Erdmenger (1954) conceived the exact geometry that leads to perfect wiping of the screw profile in a co-rotating twin-screw extruder. During the last few decades, this technology has revolutionized plastics processing in the same way a personal computer transformed information processing. Many manufacturers making devices with competing technologies have changed their products to co-rotating technology. While a counter-rotating extruder becomes a positive displacement "plug" flow device, a co-rotating extruder works similar to a single screw with some unusual features. It offers an opportunity to work on the material by the application of forces that shear or smear the material, elongate, re-orient, compress or fold the material while retaining the control over the time the material is subjected to this rigor. There exists certain limits for shear rates or strain with respect to one or the other type of stress field, but such limits are in the neighborhood of the desired values. The overwhelming influence of shear is a decisive factor. Some applications benefit from high shear rates while in others, it is detrimental. This work focuses on the beneficial effects of shear particularly in mixing and melting. Effects of the other forces such as extensional, specific aspects of reactive extrusion and efforts to reduce shear influence are not being dealt with here.

Fundamental Concepts in Mixing: Separation of bundles, size reduction of agglomerated particles, uniform distribution (establishing homogeneity) and wetting or impregnation of immiscible constituents in the matrix are the most common terms used in describing mixing requirements. Unfortunately, the usage is severely corrupted. For example, the term dispersion is used for all aspects of mixing including wetting. Essentially, requirement of size reduction or multi axial separation of agglomerated particles is referred to as dispersion or dispersive mixing. Separation of bundles without attrition of fibers is referred to as distributive mixing. The last two aspects namely establishing homogeneity and wetting is normally referred to as kneading. The essential aspect of kneading is to completely surround every individual immiscible particulate matter with the wetting medium in a manner that ensures the composition of the smallest required volume in the material is the same as the entire volume of the material. In every section, the material appears the same to the naked eye as well as microscopic examination. Wetting results in establishing a weak bond such as Vanderwaal's bonds or polar bonds that may need to be strengthened by stronger bonds generally called as coupling. Michler (1998) provides evidence of such coupling seen in Figure 1. Inadequate or incomplete size reduction and re-agglomeration are common problems experienced in dispersive mixing. Attrition or loss of fiber length and lack of wetting is the usual problem in distributive mixing.

Enthalpy of Melting & Mixing: Tadmor.et.al (1979) in their book on principles of polymer processing states that melting of compressed polymer particulate solids such as powders, pellets, beads, flakes, and granulates is the most important elementary step in polymer processing. The minimum total heat input to reach the temperature known as the processing temperature that facilitates the insertion of constituents in the matrix (or seen differently - impregnation of immiscible material by the wetting medium) is the enthalpy of melting. Additional heat (or mechanical energy) input is required for mixing. Therefore, enthalpy of mixing includes the enthalpy of melting. Heat energy required for melting is polymer dependent giving an indication of bonds that are being loosened to introduce the newer ingredients. Specific Energy is commonly used term in this context. It is defined as the total input energy per unit mass of material to accomplish the mixing task. Importantly, in modern co-rotating twin-screw extrusion, the heat exchange between the vessel and the material is so small and can be ignored. The specific mechanical energy input based on the motive power provides enough information on the process.

Kinematics of Melting & Mixing: Molecular agitation results in increase in temperature. Mixing needs such an agitated state. Shear facilitates the transfer of gross movement into molecular agitation. Shear is defined as the time duration the material experiences a given magnitude of shear rate along a particular direction. Certain requirements such as size reduction are achieved at certain shear rates. The geometry and configuration of elements affects the transfer of material and shear experienced by the material during the extrusion process. Melting and mixing is affected by the intensity as well as uniformity of shear. Uniformity refers to a narrow distribution in the volume fraction of material experiencing the same magnitude of shear.

Capability enhancement in Melting & Mixing: Shear rate is directly proportional to speed of rotation of the extruder. Change in diameter for a constant flight depth / diameter (h/d) ratio does not affect the shear rate. The clearance between the element's outer-diameter and the barrel's internal diameter influences the peak shear rate and a small volume fraction experiences such high rates leading to most common processing problems. Figure 2 shows the effect of geometry and the potential effect of clearances on the shear rate. Figure 3 shows the range of residence time possible in a co-rotating twin-screw extruder with a higher flight depth (Do/Di = 1.71) and high torque capacity (Specific Torque = 17.0 Nm/cm^3). The residence time in the extruder is independent of the speed of the extruder. It is possible to change the energy input and the type of work done by varying the time spent in various zones as detailed in Figure 4. Some interesting applications become possible by reducing residence time to less than 10 seconds. The challenges are to engineer small extruders to have high torque ability, high intake capacity and high venting capacity. Such engineering activity improves the process capability and each step along the way has raised the possibility of new applications.

Conclusion: The co-rotating twin-screw extruder is a versatile device for material preparation. The earliest generation extruder had mean residence time of 300seconds During the course of the last 50 years, the residence time has been reduced to half its original value every ten years or so. The current generation extruders have the capability to reduce the time to less than 10 seconds. A good understanding of the forces experienced by the material inside the extruder helps in precise control over the process to achieve the exact results that are required from the process. Understanding the physics and visualization of the process allows for better utilization of the co-rotating twin-screw technology. A comprehensive mathematical model will provide the required clarity and is being pursued with great vigor.

References:

1. Booy M. L (1978), Polymer Engineering and Science, Sep 1978
2. Erdmenger R (1954), U.S. Patent 2,670,188 Feb. 23, 1954
3. Englich, Sascha (2007), "Influence of the Screw Geometry..", Master's Thesis, U. Chemnitz
4. Michler G. H (1998), Kunststoff – Micromechanik; Hanser Fachbuch 1998
5. Padmanabhan (2004), U. S. Patent 6.783,270, Aug 31, 2004.
6. Padmanabhan et al (2005), "Effect of Element Geometry…", ANTEC 2005.
7. Tadmor et. al. (1979), Principles of Polymer Processing, John Wiley, N.Y.

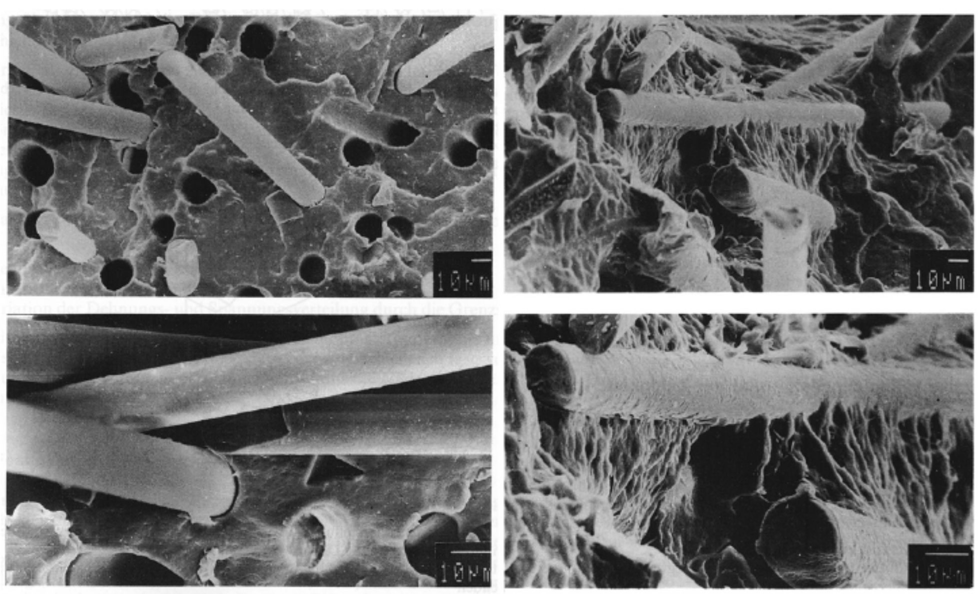

Figure 1: SEM Pictures of Glass Fiber Wetting & Coupling

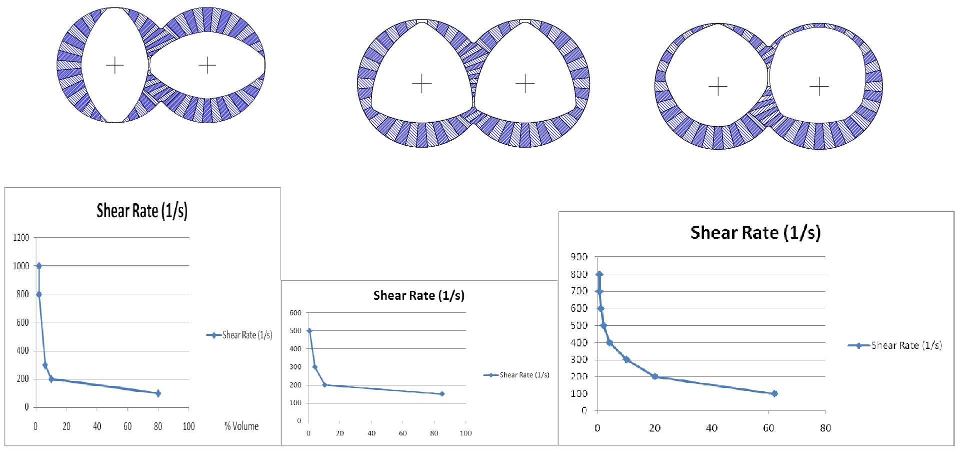

Figure 2: Radial shear rate experienced by volume fraction in a fully filled zone

Output in kg/h	Output in g/min	Mean Residence Time (s)
2	33.3	607.5
5	83.3	243.0
10	166.7	121.5
25	416.7	48.6
50	833.3	24.3
75	1250.0	16.2
100	1666.7	12.2
125	2083.3	9.7
150	2500.0	8.1
175	2916.7	6.9
200	3333.3	6.1

Figure 3: Mean Residence time in a 25mm 40 L/D (Do/Di = 1.71) extruder with 75% degree of fill.

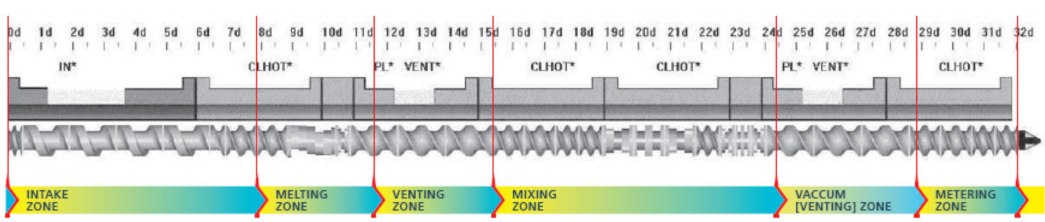

Figure 4: Process Zone in a Co-rotating twin-screw extruder