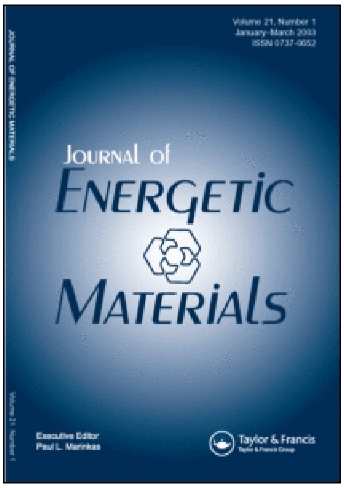

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# Safety in Design and Manufacturing of Extruders Used for the Continuous Processing of Energetic Formulations

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# Safety in Design and Manufacturing of Extruders Used for the Continuous Processing of Energetic Formulations

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*Extruders used for the continuous processing of energetic materials require various types of safety features and thus are differentiated from the extruders commonly available to civilian industries. Items of particular importance to the user include the in-process volume, control of the energetic material properties (especially temperature and pressure), the ability to quickly release pressure, reduction*

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*of metal-to-metal contact, and the control of electrical discharge. In this article, two novel extrusion platforms, the first one involving a flexible manufacturing platform and the second designed to process nanoenergetics, are described to illustrate the procedures necessary to design extrusion platforms for energetics manufacture. Particular emphasis is given to the safety features that need to be incorporated during the design stage, along with a detailed discussion of the flexibility and ease of use of extrusion equipment. The use of material-specific mathematical modeling in the design of the extrusion platforms is also elucidated as a first line of defense for safety and ease of use.*

**Keywords:** extrusion, nanoenergetics, processing, safety, simulation, twin screw

## Introduction: Continuous Processing of Energetics

While Ko-Kneaders and Rotofeeds have been successfully utilized for the continuous processing of energetic materials, largely, the production of energetics in the United States has been confined to batch technology. There is a very large investment in batch processing technology which is under utilized. This has been a significant economic barrier to investing in new technology until recently when continuous processing demonstrated significant improvements in product quality, the ability to make products that could not be made efficiently using batch process and the imposition of environmental requirements that are more easily met with continuous technologies. Interest in continuous production has been increasing, but this interest has been limited to development over the past several years. As technology has improved in many areas, a renewed interest in continuous processing of energetic materials has gained momentum in the United States. Some of the major advantages to be derived from continuous processing are higher production capacities, while maintaining lower in-process inventories; the economics of lower installation and operational costs; more uniform product quality; and lower personnel contact with hazardous materials.

The twin-screw processing system is capable of direct in-line extrusion of a product into a final geometric form. This negates the requirement for additional separate, stand-alone ram extrusion systems for forming energetic products. Reducing the reliance on multiple pieces of hardware for additional process steps reduces the handling of the energetic material dramatically, thereby reducing the exposure of labor to large quantities of energetic materials and thus reducing the overall risk of manual handling–related incidents. Furthermore, by minimizing the operational steps and handling, there are fewer processing variations. This results in a more uniform product with consistent performance.

Continuous processing technologies are also inherently safer than the batch processing methodologies because of the small amount of the energetic material found in the confines of the processor at any given time during the manufacture. For example, at the same production rate on a per hour basis, while a 1000-gal mixer would contain typically about 700 gallons of energetic material, the twin-screw extrusion system would have only tens of pounds of energetic material within the confines of the extruder. Furthermore, the drag-based pressurization in the twin-screw extruder in conjunction with the relatively small quantity of material within the mixing volume allows for processing of extremely viscous mixtures without the potential for overburdening the drive, which typifies batch mixing. The ability to easily mix and convey highly filled mixtures leads to the utility of this equipment for increasing solids loading in composite explosives and propellants.

Continuous processing technologies are also more amenable to the better control of the properties of the propellant since the surface-to-volume ratio of the continuous processor is orders of magnitude higher than the typical batch processors used in conventional processing, thus making it easier to achieve relatively homogeneous temperatures and degree of distributive and dispersive mixing during manufacture. Furthermore, continuous processing technologies like the twin-screw extrusion process have the added benefit of flexibility since the screw and barrel sections are generally modular and interchangeable, thus providing a myriad of geometries for processing of energetics, with each screw and barrel configuration representing a different processor. Twin-screw processors are so flexible that they have been used to process energetic materials with processing shear viscosities in the low shear rate regime from 2,000 to 1,250,000 poise. This range of materials cannot be processed effectively in any single batch mixer.

However, the opportunities offered by the continuous processes like the twin-screw extrusion process come at the price of necessitating extensive rheological characterization [1–18] and simulation and structure characterization tasks prior to the processing of the first pound of the propellant [19–26]. Such characterization uses specialized techniques to characterize the rheological behavior, including the characterization of the viscoplasticity and the wall slip behavior of the energetic material, thermal properties, decomposition characteristics, the conditions under which the particles or the binder of the energetic suspension migrates or filters out, means to keep the air out, development of surface irregularities, and analysis for the degree of mixedness of the ingredients as part of the characterization of the energetic formulation [1–18]. This is especially necessary considering that unlike other industries, which also utilize continuous processors, trial-and-error procedures cannot be used in the energetics industry. The wrong marriage of geometry, operating conditions, and material properties will invariably result in an incident.

Some of the preliminary characterization tasks that are necessary in the development of a continuous processing technology for the manufacture of energetic formulations include thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) analysis, the characterization of various material functions, including temperature and wall shear stress–dependent shear viscosity, extrudate swell, flow instability and wall slip behavior of the energetic formulation, the simulation of the coupled flow and heat transfer occurring in the twin-screw extruder, the design of the shaping geometry including the die, and validation experiments generally using thermal imaging and well-instrumented twin-screw extruders. Such characterization and simulation tasks are essential to the safe processing of energetic materials, which can be accomplished without the use of precarious trial-and-error procedures.

## Operation and Safety Features

Designing mixing equipment that answers the needs of today's energetic material producers requires an in-depth understanding of the safety and performance problems facing this industry. The hardware needs to be designed on the basis of various criteria that recognize the safety concerns without compromising performance. Here two extruders will be used as examples for illustrating the integration of safety into design and manufacture of continuous processing machinery. These two extruders are interesting because the first one (ME 7.5) is, to our knowledge, the smallest twin-screw extruder in the world, designed specifically for the incorporation and processing of nanoparticles in energetics formulations [27] and the second is the universal, which is the most flexible manufacturing platform for energetic materials, with the ability to be converted into a single- or twin-screw, corotating or counterrotating extruder [27]. The intermesh between the two screws in the twin-screw extruder mode can be altered to any degree of intermesh ranging from the tangential to the fully intermeshing mode (universal mixer/extruder). Furthermore, the barrel is splittable with a hydraulic mechanism that can sustain internal pressures of up to 5,000 psi and the sensor, feed, vacuum locations, as well as the total length of the extruder, can be altered to fit the processing task at hand [27].

Safety becomes even a greater concern with the necessity to process without organic solvents, using binders that are themselves energetic and with nanoparticles with their very high surface-to-volume ratios. The decomposition characteristics of some of the relatively new materials are also a cause for worry.

## Design Development and Safety Issues

In general, the following summarizes how the extruders work and how the principal design of the geometries is made. Product ingredients enter the machine through various feed ports. The product passes to the conveying screws, where it is carried from the drive end to the mixing section. A custom-tailored agitator section (generally material specific and designed using mathematical modeling employing 3-D finite element method [19,24–26] then alternates product mixing and thermal conditioning until the product is fully homogenized and reaches the desired temperature. The product then moves to the vent section for devolatilization. Next the mixture moves into the discharge section, where pressure is developed to extrude the product through a die to develop a continuous geometric form.

These unique pieces of processing machinery, though based on twin-screw polymer processing compounders, were specifically designed for use in the continuous manufacture of energetic materials. Therefore, they differ from polymer processing machinery commonly used in the marketplace today in a considerable number of ways. Aside from the ability to properly mix and extrude a variety of energetic materials, the prime consideration in design was, and is, safety. As noted earlier, the energetics industry cannot tolerate the use of trial-and-error procedures since wrong guesses lead to incidents, and the ability to predict the coupled flow and heat transfer to occur in the extruder at the design stage introduces a significant capability to assure the safety of the process [19,24,26].

## *Mini Twin-Screw Extruder ME 7.5 for Processing of Nanoenergetics*

The ME 7.5 (Figs. 1, 2) was designed using mathematical modeling and was built initially for the distribution and coating of nanoparticles [27]. The twin screws have a diameter of 7.5 mm (Fig. 1) and are corotating, fully intermeshing, and self-wiping with an L/D of 15/1. Typical distributions of velocity, pressure, shear rate, and temperature for the processing of an energetic thermoplastic elastomer–based compound in the first mixing zone and the slit die of the mini twin-screw extruder are shown in Figs. 3–6. These cover the distributions of shear rate, i.e., the second invariant of the rate of deformation tensor (Fig. 3); the distributions of the second invariant of the stress tensor and

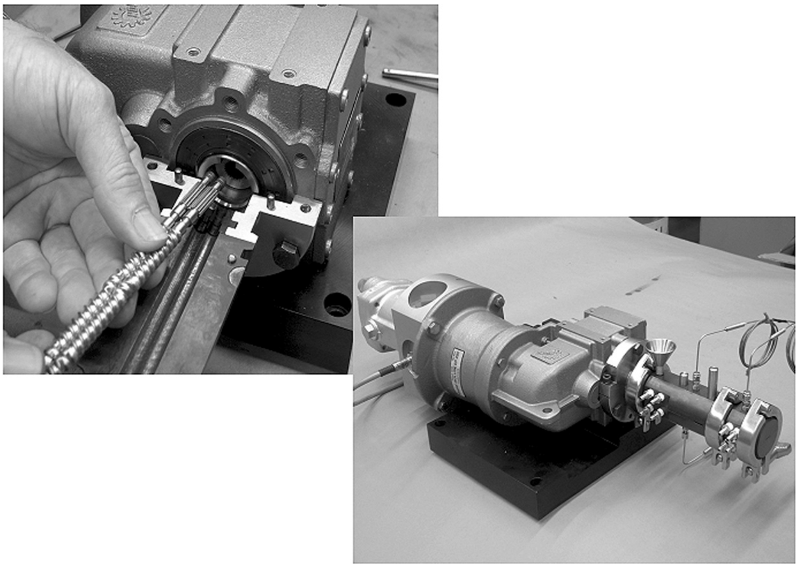

**Figure 1.** Mini extruder specifically designed for processing of nanoenergetics.

distributions of the component of the velocity vector in the main flow direction (axial, z-direction; the integration of which over any x-y cross-sectional area provides the volumetric flow rate; Fig. 4); and the pressure and velocity distributions in the die (Figs. 5 and 6). The design thus relies right from the beginning on knowledge of the detailed thermomechanical history that the target formulation is to be exposed to during processing. The entire processing operating condition space can be probed to determine if there are precarious conditions under which the energetic formulation will develop stagnant ‘‘dead’’ zones, or hot spots, which will generate temperatures that are greater than the decomposition temperature of the energetic material, and open channel flows that will give rise to the passage of the material through the extruder without intermixing with the rest of the ingredients.

The degree of fill in the extruder is also determined as a function of the possible operating conditions. This is especially

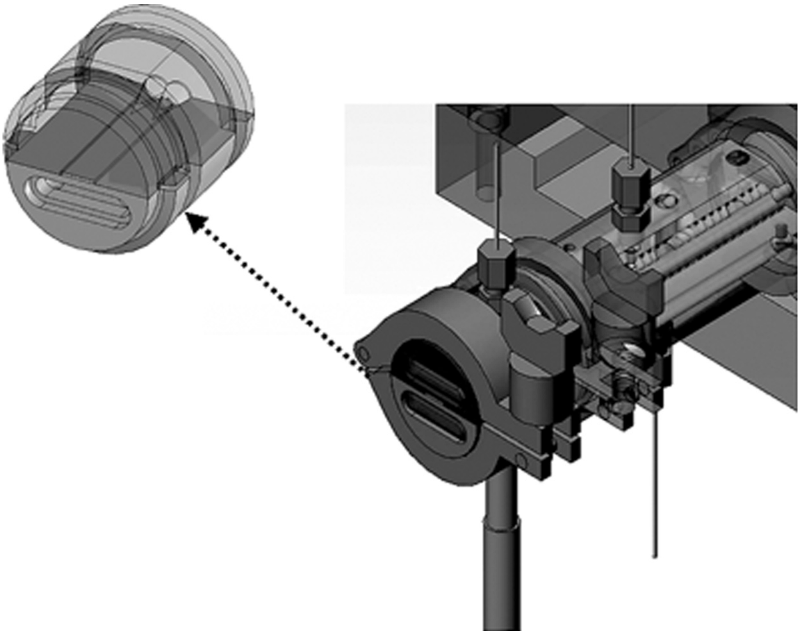

**Figure 2.** Slit die of the mini twin-screw extruder.

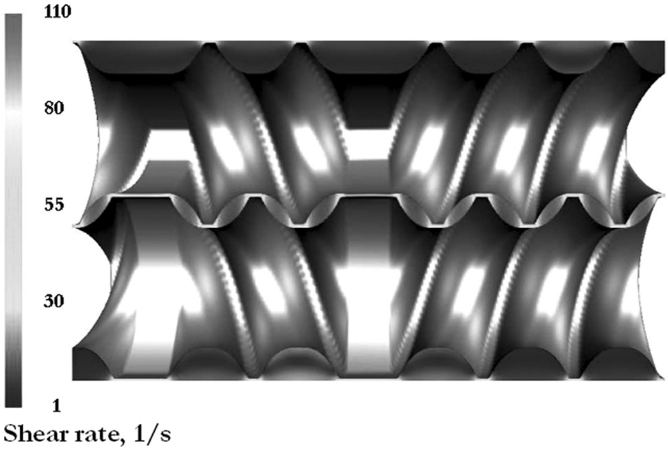

**Figure 3.** Shear rate distribution at the first mixing section for 0.05 lb/h and at 105°C.

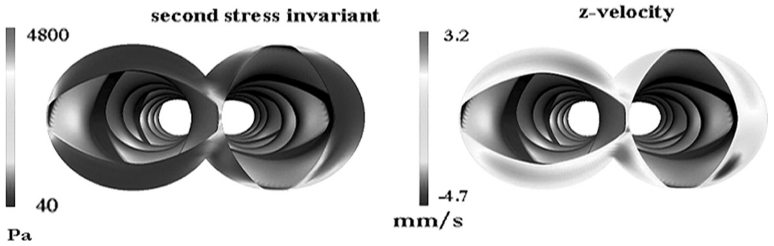

**Figure 4.** Second stress invariant and axial, z-velocity distributions at the first mixing section for 0.05 lb/h and at 105°C.

crucial since for a given set of operating conditions the energetic material should not back up into the feed hoppers or into the vacuum port. Thus, overall the mathematical modeling of the processing operation for a target formulation allows the design of the machine to be tailored and precarious geometry/operating condition combinations can be eliminated at the design stage. The ability of the extruder to process the given formulation is also fully assessed to recognize what the maximum and the minimum flow rates are to be and what the distributions of residence time, shear rate, pressure, and temperature are to be in the twin-screw extruder.

The ability to select the screw configuration on the basis of mathematical modeling of the process for a target formulation

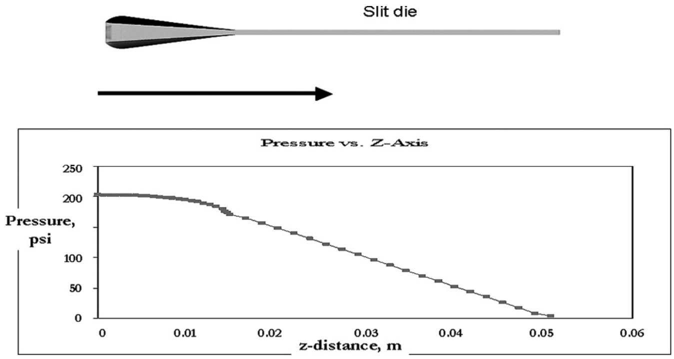

**Figure 5.** Pressure versus distance at the slit die for 0.05 lb/h and at 105°C.

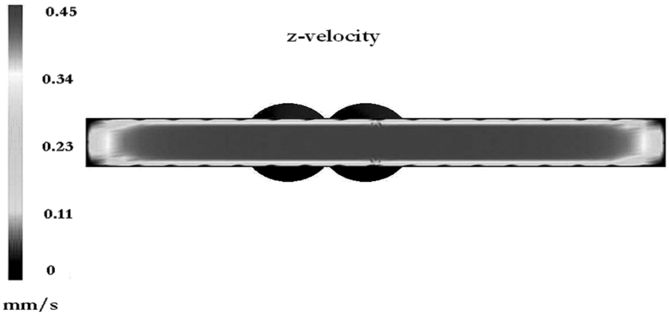

**Figure 6.** Typical axial, z-velocity distributions at the slit die for 0.05 lb/h and at 105°C.

is again important, especially considering that many safety departments will not allow segmented screw components and will insist on the use of solid screw agitators. Also for the 7.5-mm twin-screw extruder shown in Fig. 1 the screws are so small as to not permit the use of slip on elements and the entire screw needs to be machined in one piece. The utilization of the simulation technologies allows the designing of the proper screw configuration right from the beginning, thus providing not only safety of knowing to what thermomechanical history the energetic material is to be exposed to but also savings in cost and schedules by eliminating the trial and error necessary otherwise for the screw design. The ability to model the coupled flow and heat transfer associated with the processing of a particular product in a twin screw also enables the engineer to explore optimum solvent conditions for both processing and safety. Selecting the lowest solvent concentration for safe processing reduces the environmental impact, cost, and time/energy required to dry the product.

It is also important to recognize that the thermomechanical history that the energetic material will be exposed to in the extruder will also depend on the geometry of the die to be used. The flow and temperature history in the extruder is directly affected by the presence of the die since the extruder will generate only the pressure necessary to overcome the pressure drop at the die [19]. The pressurization rate and thus the degree of fill are functions of the die used. Thus, the mathematical problem needs to be solved as a coupled flow and heat transfer problem covering both the extruder and the die [19]. One of the die designs used for the mini is shown in Fig. 2. This is a rectangular slit die designed to produce rectangular extrudates, which can then be used for the testing of the nanoenergetics grain. The typical results of pressure distribution and the z-velocity distribution over a cross section of the die are shown in Figs. 5 and 6. Thus, the design of the die is an integral part of the design of the extruder for the processing of the energetics formulations. The change in the shape of the flow channel in the die will generate a different extruded grain shape.

### ***Universal Extrusion Platform***

The universal extrusion platform (MU 40; Fig. 7) can be operated as a single-screw extruder, fully intermeshing corotating twin-screw extruder, fully intermeshing counterrotating twin-screw extruder, tangential corotating twin-screw extruder, or tangential counterrotating twin-screw extruder [27]. One of the configurations involves twin screws with a nominal diameter of 40 mm and the length of the machine is variable in 5/1 L/D sections up to 40/1 L/D maximum. However, depending on the nature of the application, the extruder can be custom designed for other sizes also. In Figs. 8–11 the distributions of velocity, pressure, and temperature for a tangential counterrotating twin-screw extruder configuration for an energetic material are shown. The die used is again a slit die, which can generate rectangular extrudates. The ability to determine conditions that are potentially hazardous and the weeding out of these conditions at the design stage are again emphasized by these results. These typical FEM-based simulation results pertaining to a mass flow rate of about 72 lb/h of an energetic composition suggest that the details of the thermomechanical history can indeed be determined. Additionally conditions that are precarious can be recognized and the wrong marriages of geometry, operating conditions, and material that lead to

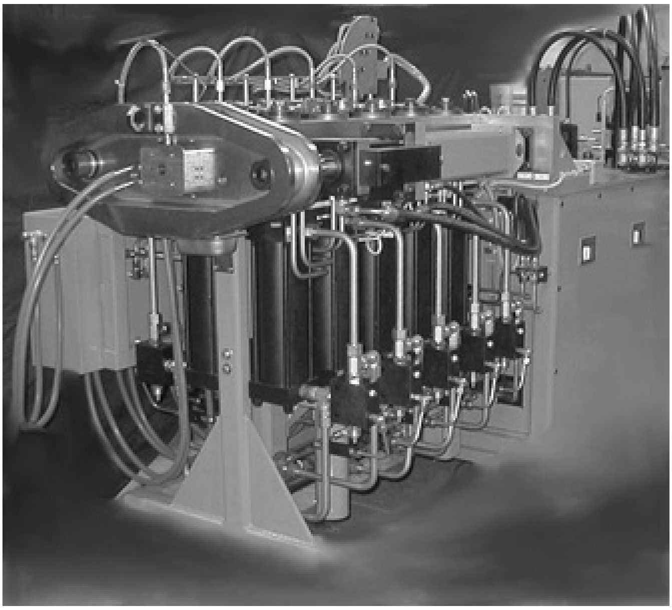

**Figure 7.** Universal extrusion platform with the hydraulic cylinders shown.

**Figure 8.** Pressure distribution at the die and pressurization section of the universal twin-screw extruder for 100 rpm, 180°C, and 72.3 lb/h.

**Figure 9.** Axial, z-velocity, and temperature distributions at the die and pressurization section of the universal twin-screw extruder for 100 rpm, 180°C, and 72.3 lb/h.

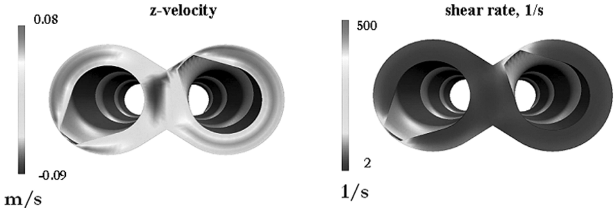

**Figure 10.** Axial, z-velocity, and shear rate distributions at the die and pressurization section of the universal twin-screw extruder for 100 rpm, 180°C, and 72.3 lb/h in the transverse to flow direction.

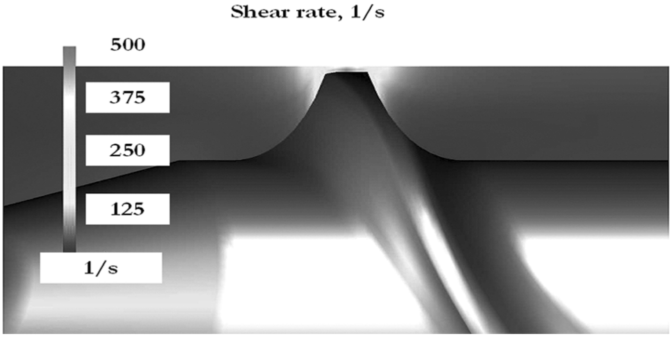

**Figure 11.** Shear rate distribution at flight barrel interface of the universal twin-screw extruder for 100 rpm, 180°C, and 72.3 lb/h.

safety concerns can be eliminated before the processing of the first pound of the energetic material.

The specific requirement for the power capability can also be determined using mathematical modeling of the process for the target formulation. Closely allied with specific horsepower requirement is residence time of mixture within the process zone. Typically, residence times of 30 s to 20 min are observed, dramatically improving safety over batch mixing operations.

Dispersive mixing implies that changes occur in the physical properties of the ingredients of the formulation including the breaking apart of agglomerated materials. Distributive mixing, on the other hand, implies the even apportioning (spatial rearrangement) of each phase and ingredients of the final product. In the twin-screw mixer, studies have indicated that depending upon the addition sequence and salvation kinetics, appropriate mixing normally occurs within 15% of the available processing area, the remainder of which becomes available for forwarding, shearing, deaerating, and consolidating the mixture.

The ability to devolatilize and/or deaerate an energetic formulation is of considerable importance due to the degenerative effects of such entrapments of gases, including air, on mechanical properties and sensitivity. Various studies [22] show that because of the low volume-to–surface area ratio and the rapid exposure of fresh mixture to the vacuum source, deaeration and devolatilization of mixtures are more complete in this type of equipment than in batch-type processors. This enhances the safety of the process.

## Specific Safety Issues and Corresponding Design Features

### *Issue: Temperature Control*

One of the primary safety issues related to processing of energetic materials is the requirement for precise control of the temperature of the energetic material. The most critical parameter for safely processing energetic materials is the ability to control the temperature of the product, both the apparent mass (or bulk temperature) as well as localized temperature, especially due to viscous energy dissipation.

The twin-screw mixer converts the mechanical energy of the rotating screws into heat through shear and extensional deformations generated within the carefully maintained clearances between the screws and between each screw and the barrel housing. The viscous energy dissipation is directly related to the deformation rate and the shear viscosity of the mixture (scales with the square of the deformation rate and directly proportional to the local shear viscosity). The shear viscosity of the mixture changes with increasing degree of mixedness of the ingredients of the formulation (as a function of the total specific energy input) [5,20]. As the shear viscosity of the energetic formulation being processed is also a strong function of temperature, it is essential to control the temperature at various sections of the extruder. These extruder sections include the feed zones, mixing zones, deaeration zone, discharge zone, and, when used, the extrusion zone and die head assembly.

The temperature of the energetic formulation should not be allowed to reach the decomposition temperature of the formulation. However, the highest temperatures occur in the midst of mix where thermocouples cannot measure the temperature. Thus, since there is no way one can measure the formation of the hot spot in the extruder during the processing operation, one needs to predict and eliminate conditions that lead to hot spot temperatures that reach the decomposition temperature of the formulation, following the simulation route outlined earlier. Modeling has the potential of accurately predicting decomposition conditions and where they will occur. Various real-time data including the screw rpm, torque, and temperature measurements along the barrel and at the die should also be monitored and used to determine if there is an excursion into conditions that may result in dangerously high temperatures.

In addition to optimizing the agitator profile for a specific process, extruder designs incorporate the largest possible liquid media channels for the thermal conditioning of the process by providing the greatest possible surface area–to-volume ratio within the barrel envelope. Independent multiple zone controls and in-process monitoring instrumentation are employed at strategic locations throughout the length of the barrel and at the die. In addition to utilizing these sensors to monitor and control the process temperatures, they can be used for emergency equipment shutdown and to trigger a high response rate deluge system for the equipment. IR and UV detectors can also be installed as part of the equipment system for triggering a deluge system.

Another important contributor to control of heat buildup addressed is the ability to control horsepower. A specially designed hydrostatic drive controls speed and torque and affords the flexibility to finitely control process energy input. Finally, on the universal extruder the torque on the two shafts can be determined directly and separately using slip ring technologies [27]. The torque per shaft is the shear stress integrated over the entire surface area of the screw and thus is intimately related to the degree of fill in the extruder and the shear stress generated by the energetic suspension. Alarms, as well as torque-related automatic disengagement mechanisms, are incorporated into the design of the universal extruder as additional safeguards.

## *Issue: Control of Product Pressure*

Pressure control is another area of special interest, especially because many materials require pumping through a die assembly or through reversely configured screw elements under large consolidation forces. Also, the pressure increases in regions such as the feed zone or near shaft seals indicate undesirable conditions. Closely related to the critical characteristic of process temperature control is the requirement to keep the product within desired pressure limits, especially in the pressurization zones of the unit. Pressure control is required to eliminate the possibility of intergranular shear and to preclude seal leakage due to loading created by product upsets (i.e., die blockage, feeder or pump failures, etc.). Reliable pressure control also enables the use of automated control to vent the machine if safety limits are exceeded. In addressing this safety issue, these extruders feature computerized optimization of the discharge screws that ensure design extrusion pressures that are met with a minimum 50% safety margin on degree of backfill of the screws. During processing, pressure transducers monitor internal barrel pressure at critical points and will trigger shutdown of the unit if preset safety limits are exceeded. As with the temperature sensors, the pressure sensors can be used to trigger a deluge system.

### *Issue: Electrical Discharge*

The potential of ignition due to electrical discharge is another area of concern when processing potentially hazardous material such as energetics due to the electrical sensitivity of many of the formulations. In addressing this potential safety issue, the design of these systems is such that all electrical components in the mixer area are either fully explosion proof to Class I group D and Class II groups E, F, and G standards or are intrinsically safe as per the National Electric Code (NEC). By definition from the NEC, intrinsically safe equipment and wiring shall not be capable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of flammable or combustible atmospheric mixture in its most easily ignitable concentration.

In the design of the two extrusion platforms, hydrostatic drive systems were used, which put the primary electrical power source outside of the mixing area in a non-hazardous environment. The torque pickup device on the drive motor as well as all the temperature and pressure transducers on the mixer proper must be intrinsically safe. In our designs, the hydrostatic power unit utilizes a special polyol ester–based synthetic fire retardant fluid that is classified as non-hazardous. The drive is designed to be unidirectional to prevent the inadvertent startup of the machine in the reverse direction.

Thermal conditioning for the hardware is accommodated via liquid media circulated through cooling channels in the barrels. The media conditioning systems are remotely located from the process in a non-hazardous area.

Additionally, the ME 7.5 machine is small enough that the entire machine and the ancillary components supporting the process can be placed in a hood to optimize safety. A typical processing rate for this unit is around 10–100 g per hour. The equipment is supplied with grounding lugs to dissipate static electric charge before it can build up on the machinery.

### *Issue: Metal-to-Metal Contact*

Frictional ignition of the product due to dynamic metal contact is a concern for the processing of energetic materials. Experience has shown that the hydrodynamic film of the product will support the screws off the barrel surface in most applications. However, under certain conditions, the film can break down and metal contact can occur (especially for formulations that lack elasticity as manifested by relatively low first normal stress difference values determined upon simple shear flow during rheological characterization). When this happens, it is desirable to have the barrels and screws manufactured from materials that prevent adhesive wear. For example, for the ME 7.5 and the universal, the screws and barrels of these units are manufactured from a through-hardened stainless alloy that is specifically designed to resist wear and corrosion. They are then treated with ferritic nitro carburizing that changes the surface of the metal for several thousands of an inch in depth, imparting a greater hardness to the metal at the surface and reducing its coefficient of friction. This reduces the possibility of any metal-to-metal pickup and greatly reduces the energy generation from any contact of the screws to the barrel bores.

Screw speed is a concern because of the possibility of reaching tip speeds exceeding the friction sensitivity of energetic oxidizers or imposing a high viscous shear heating load. Additionally, at a given torque and throughput rate, the localized heat transfer capacities of energetic binders and plasticizers may be self-limiting factors. It is generally assumed best to operate at the lowest possible screw speed necessary to achieve the mixing and consolidation of phases required by mechanical property constraints. However, maintaining the shear required to maximize binder-filler interaction at any screw speed occurs when the mixture is processed at maximum torque. Consequently, at the design stage a hydrostatic drive unit is selected as the optimal drive for meeting these requirements.

The thrust bearing and seal assembly for the ME 7.5 machine is manufactured from a carbon fiber–reinforced electrically conductive polymer and precludes any metal contact with the agitator shafts at the drive end of the machine. The screws are supported at the drive end by sealed antifriction bearings, which are located outside of the seal area. The 40-mm universal has thrust bearings mounted in the gear box, remote from the barrel assembly, that are separated from the process material by seals and a considerable air gap. The screws are supported on the drive end by antifriction bearings mounted in the gear box.

## ***Issue: Maintenance***

Another safety consideration is maintainability and good housekeeping characteristics of the processing machinery for energetics manufacture. In addressing the particular use for any equipment, it is obvious that cleanliness and the prevention of contamination are essential parts of the safety considerations. In addition, safe maintainability at the design stage has to be considered a high priority as it is evident that personnel will be required to clean and disassemble the unit after shutdown from live material runs or if a system fault occurs.

Addressing this issue, the following design features were incorporated into our designs. In the fully intermeshing mode, the screws in the mixing and extrusion area are fully conjugal; that is, an arc on one agitator fully describes the surface of the mating agitator through a 360-degree revolution. Hence, the screws completely wipe each other and the barrel bores within the clearances prescribed. From a process standpoint, this assures that the surfaces are completely regenerated of product, but possibly as important, it means that the machine is internally self-cleaning and will purge itself of product when run after the purge feeders are shut off. There should be no stagnation areas in the machine. Orifice plugs and other devices sometimes used in polymer processing to restrict flow are avoided in the design of extruders for energetics manufacture. This is to ensure that no voids or pockets, which could entrap material in the unit, are present. Entrapped material may become partially cured and then form a mass of material that can be pinched between the processing elements or the wall creating a safety hazard.

The mini extruder designed for the processing of nanoenergetics, ME 7.5, features a horizontally split barrel and die assembly, which is held together by quick release clamps. The barrel and die assembly also separate vertically for ease of cleaning. The barrel separates from the drive assembly via the same quick release clamps. The agitators can be removed from the machine by the use of a release mechanism that does not require the use of tools (Fig. 1). The drive sleeve, which holds the screw shafts in the machine, is slid back after it is released outside of the process area via a spring-loaded detent system. When this sleeve is moved, it releases the agitator shafts from the radial and thrust bearing assembly and they can then be removed from the machine. This process can be accomplished without the need for special tools in the product area.

To eliminate cracks and crevices, the ME 7.5 agitators are of a monolithic design. They are precision tooled from solid bar stock, thereby yielding better torsional and bending strengths versus segmented designs for these small diameters. The solid agitators are designed and custom built for each application via computer modeling.

While slip-on elements are highly suited for testing a wide variety of formulations, the equipment designed to process a given energetic mixture need not offer such flexibility, because once process parameters are established for a steady-state operation, no adjustments should be necessary. Furthermore, a fixed agitator configuration may be used for mixtures requiring different treatments through control of such variables as temperature, screw speed, torque, and residence time. This conclusion is based not only on mathematical modeling but also on data gathered by observation when dead stops are performed during operation.

The 40 mm universal features barrel sections that are horizontally splittable (Fig. 7). The barrel can be separated at the horizontal split line and the entire upper barrel section opened via the hydraulic power unit for ease of cleaning and maintenance. This also allows for easy access to change out and recon figure the screw assemblies. The barrel sections are electrolysis nickel-plated on the exterior surfaces to aid in cleaning and to prevent corrosion of the components. The design calls for internal melt pressures that can be as high as 5,000 psi.

Additionally, the ability to access the equipment via the split barrels on both designs enables the operators to perform dead stops. Dead stopping is a process that allows for important observations and data gathering when the machinery is stopped in a step fashion and disassembled during steady-state operation. This information can be used to validate the predictions of a model if one is being used. Typically, when running inert formulations, this allows the operator to peer into the process zone in search of otherwise difficult-to-determine information, such as stagnation, metal-to-metal contact points, leakage paths, and percentage fill of various portions of the process zones. This information can also be used during development to verify data predetermined from the three-dimensional mathematical models.

## *Issue: Process Control and Data Acquisition*

The acquisition of process data and control of the process as well as safety parameters are critical features of the continuous processing equipment design. Both extrusion platforms are operated via a state-of-the-art open architecture PC-based system that includes full instrumentation to monitor and control zone temperatures and screw speed and monitor product temperatures, process pressures, and screw torque. The software allows remote operation of the units as well as remote data collection, either wireless or via the Internet in conjunction with field point technology. All of the safety features are programmed with automatic shutdown for over-temperature, overpressure, or over-torque of the system. Mechanical safety backup for over-torque in the form of a quick-response, high-flow relief valve is an integral part of the hydrostatic drive system on both units.

### *Additional Features*

In addition to the major safety features described, other design features that contribute to safer operation and also optimize some of the processing versatility of the equipment are

- ample mechanical safety margins in design
- infinitely variable speed control throughout the designed operating range
- over-torque shutdown protection
- integral and complete hydraulic system for the barrel top opening on the 40-mm universal
- integral and complete hydrostatic drive system
- design for full vacuum as well as internal pressure
- injection ports in the barrel for the introduction of liquid additives
- multiple feed ports for solids addition
- corrosion resistant enhancement for the agitators and barrels.

## Conclusions

The prime design consideration for the development of extrusion technologies for processing of energetic formulations is safety. All the features mentioned in this manuscript lend themselves to the safe application and operation of extrusion equipment for these types of applications. Furthermore, the geometry and operating conditions need to be selected judiciously, preferably upon rigorous mathematical modeling of the coupled flow and heat transfer to occur in the confines of the extruder for a given energetic formulation. The initial characterizations of rheological and thermal properties are essential for such mathematical modeling of the process to understand the thermomechanical history that the energetic material will be exposed to during the processing stage.

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