Pulverization of Rubber Using the SSSE Process



Barry Bernstein, Ecevit Bilgili, Hamid Arastoopour

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Outline of the presentation

- Motivation behind our pulverization and recycling study
- Production, characterization, and reuse of a rubber powder:
 - Concepts of the solid state shear extrusion (SSSE) process
 - Experimental and computational heat transfer study

Summary



Motivation behind this study

- More than 2.5 billion scrap tires are presently stockpiled in the U.S. alone; disposal charge for rubber waste is increasing.
- Recycling methods such as microwave, ultrasonic, and thermal treatments degrade rubber significantly.
- Size reduction is a promising recycling technique. It does not severely degrade rubber.
- Cryogenic grinding produces fine particles, but is expensive. Development of a non-cryogenic technology that can produce comparably fine particles is essential.





Base-case conditions: barrel wall temperatures 135°C, 135°C, and 40°C; one pass of rubber (1SSSE) at a feed rate: 4.6 g/min; screw rotation rate: 80 rpm; compression ratio of the screw: 5:1

SSSE process: functional zones



- Geometric mean diameter of the feed was about 4.00 mm.
- Compression ratio (CR) is defined as $CR = H_{in} / H_{out}$.

SSSE process: effect of compression



- An decrease in CR led to a coarser particle size distribution.
- The geometric mean diameter and standard deviation of the powders were 0.42 mm and 2.04, 1.33 mm and 2.06, and 3.30 mm and 1.42 for the 5:1, 3:1, and 1.5:1 compression ratio (CR) cases, respectively.

SSSE process: effect of temperature



- An increase in barrel wall temperature led to a coarser particle size distribution.
- The geometric mean diameter and standard deviation of the powders were 0.42 mm and 2.04, 0.82 mm and 2.02, 1.24 mm and 2.15, and 1.83 mm and 1.91 for the T_{b3} values of 40 °C, 60 °C, 80 °C, and 100 °C, respectively.



Heat transfer in the SSSE process

- Efficient production of fine particles depends on the success of removing the heat dissipated in the extruder.
- High temperatures in the pulverization zone of the extruder can cause
 - thermal degradation of rubber particles
 - faster stress relaxation and consequent retardation of the fragmentation
 - agglomeration of the fine particles
- Efficient removal of heat is important to the scale-up of the extruder.

Experimental study: air cooling in all zones (1)



The cooling of the extruder barrel walls via compressed air is not sufficient if the screw is not internally cooled. The center of the screw is the hottest spot in the extruder.

Experimental study: water cooling in Zone 3 (2)



The cooling of the extruder barrel walls via water circulation significantly removes the heat generated. But, the high radial temperature gradient still prevails.



Modeling study: geometry of Zone 3



Modeling study: simulation for solid screw



- The model predicts the high radial temperature gradient in the extruder.
- Regions 1, 2, and 3 represent solid screw, rubber, and barrel wall, respectively.
- Simulation for 600 s of SSSE processing, water at 25 °C in the cooling jacket with h = 300 W/(m² °C)

Modeling study: simulation for hollow screw



- The use of a hollow screw within which cold water circulates is an efficient way for removing the heat generated during the pulverization.
- Regions 1, 2, and 3 represent hollow screw, rubber, and barrel wall, respectively.
- Simulation for 600 s of SSSE processing, water at 0 °C in the cooling jacket with $h = 300 \text{ W/(m}^2 \text{ °C})$, water at 0 °C in the hollow screw with $h = 300 \text{ W/(m}^2 \text{ °C})$



Summary on the SSSE process and recycling

- The SSSE process is capable of producing fine rubber particles without employing cryogenic cooling.
- The particle attributes can be tailored for specific recycling applications by manipulating the SSSE process variables.
- To lower the temperature gradient in the rubber, our simulations suggest the use of a hollow screw.

Refereed publications

Journal Publications

- E. Bilgili, A. Dybek, H. Arastoopour, B. Bernstein, "A New Recycling Technology: Compression Molding of Pulverized Rubber Waste in the Absence of Virgin Rubber," *J. Elastom. Plast.* 35, 235–256 (2003).
- E. Bilgili, H. Arastoopour, B. Bernstein, "Pulverization of Rubber Granulates Using the Solid State Shear Extrusion (SSSE) Process: Part II. Powder Characterization," *Powder Technol.* 115, 277–289 (2001).
- E. Bilgili, H. Arastoopour, B. Bernstein, "Pulverization of Rubber Granulates Using the Solid State Shear Extrusion (SSSE) Process: Part I. Process Concepts and Characteristics," *Powder Technol.* 115, 265–276 (2001).
- E. Bilgili, H. Arastoopour, B. Bernstein, "Analysis of Rubber Particles Produced by the Solid State Shear Extrusion Pulverization Process," Rubber Chem. Technol.73, 340–355 (2000).
- E. Bilgili, H. Arastoopour, and B. Bernstein, "Solid State Shear Extrusion of Rubber Granules," AIChE Symp. Ser. 95, 83–89 (1999).

Patents

- G. Ivanov, H. Arastoopour, E. Bilgili, N. Shahidi, and B. Bernstein, "Apparatus and Process for Pulverization of a Polymeric Material," U.S. Patent No. 6,513,737, Feb. 4, 2003.
- + H. Arastoopour, D. A. Schocke, B. Bernstein, and **E. Bilgili**, "Process for Recycling of Rubber Materials," *U.S. Patent No.* 5,904,885, May 18, 1999.

Modeling study: governing equations

Local energy balance for the extruder screw:

$$\rho_{\rm s} C_{\rm ps} \frac{\partial T_{\rm s}}{\partial t} = k_{\rm s} \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_{\rm s}}{\partial r} \right) + \frac{\partial^2 T_{\rm s}}{\partial z^2} \right]$$

Local energy balance for the solid plug of rubber:

$$\rho_{\rm m} C_{\rm pm} \left(\frac{\partial T_{\rm m}}{\partial t} + V_{\rm z} \frac{\partial T_{\rm m}}{\partial z} \right) = k_{\rm m} \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_{\rm m}}{\partial r} \right) + \frac{\partial^2 T_{\rm m}}{\partial z^2} \right] + \frac{\tau \omega f}{\pi \left(R_3^2 - R_2^2 \right) L}$$

Local energy balance for the barrel wall:

$$\rho_{\rm b} C_{\rm pb} \frac{\partial T_{\rm b}}{\partial t} = k_{\rm b} \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_{\rm b}}{\partial r} \right) + \frac{\partial^2 T_{\rm b}}{\partial z^2} \right]$$

We imposed 3 initial conditions and 12 boundary conditions and solved the PDEs using a finite difference method.