Abstract

For a silo design, it is very important to understand the friction characteristics of bulk solids with silo walls. This so-called wall friction angles were measured in this study with two different testers: Jenike shear tester and Schulze ring shear tester (RST). Soft PE plastic pellets A was used as the tested bulk solids while stainless steel SS 304 and aluminum Al 6061 were selected as wall plates.

It was found that the most important parameter in this study is wall roughness. With decreasing wall roughness, wall friction angles decrease no matter which tester was used. Wall friction angles for both testers were similar if wall roughness was similar. The only exception is under the testing condition of the low pressure (500 Pa) on a wall plate. In addition, the impact of testing temperatures (22 and 37°C) has been described in this study.

Keywords: Wall friction measurement, Jenike shear tester, ring shear tester, wall friction angle, wall roughness

1. Introduction

Wall friction of bulk solids is a critical parameter when designing a mass flow silo/hopper. A translatory shear tester, the Jenike shear tester, is widely used in measuring the wall friction of bulk solids. However, the Jenike shear tester is not an automated apparatus, and its testing results are operator dependent\(^1\). Schulze et. al.\(^3\) developed a new ring shear tester, which can be used to measure the wall friction of bulk solids automatically. Schwedes et. al.\(^3\) reviewed developments in the design of several shear testers, including Jenike shear tester and ring shear tester. They considered these two testers as the simpler testers to permit straightforward measurement of the flow properties used for practical applications.

In this work, the wall friction of the soft PE plastic pellets A was measured with a) the Schulze ring shear tester RST-01, and b) the Jenike shear tester. The effect of elasticity of products was not investigated in this paper.

2. Testing Methods and Materials

2.1 Ring Shear Tester (RST)

The wall friction cell of the Schulze ring shear tester is shown in Fig. 1\(^6\). To measure the wall friction using the RST, the distance between the upper surface of the wall material sample and the upper edge of the shear cell should be about 8 to 10 mm. The details on the operating procedure of RST could be found in the reference\(^4\).

Fig. 1 Jenike-Schulze Wall Friction Cell [4].
Fig. 2 shows where the shear force $S_w$ is plotted vs the shear travel measured by a ring shear tester. Relating the shear force to the normal force $N_w$, the Wall Yield Loci (WYL) can be calculated (Fig. 2 right). Typically the WYL is convex-upward. The wall friction angle, $\varphi_w$, then is, defined as:

When tests are to be conducted at elevated temperature, the solids and shear cells are heated to test temperature in an oven prior to conducting the shear test. The heated shear cell and solids are removed from the oven and placed on the ring shear tester to measure the flow properties. During a shear test, Infrared lamps are arranged around the shear cell to prevent the cooling of the shear cell during the test. At the end of each shear test, the temperature of the solids in the shear cell is checked to ensure that the temperature of the solids and the wall friction sample remained constant during the shear test.

2.2 Jenike Shear Tester

A sketch of the Jenike shear tester is presented in Fig. 3 and the procedure to measure the wall friction angle with the Jenike shear tester could be found in the reference\(^5\).

The recorded values of normal loads, $N_w$, and shear stress, $S_w$, (Fig. 3) from Jenike shear tester could be plotted as shown in Fig. 2 right (the same as for the RST). Then the wall friction angle, $\varphi_w$, can be obtained by Eq. (1). Since a wall yield locus is usually represented by a curved line, the wall friction angle varies and is a function of the pressure at the wall.

2.3 Wall Roughness Tester

A Taylor Hobson manufactured wall roughness tester (model: Surtronic\textsuperscript{TM}3+) was used to measure the wall roughness, $Ra$, for all wall plates. The typical relationship of the finishing process vs approximate range of $Ra$ values was listed in Table 1\(^6\).

\[
\tan \varphi_w = \frac{S_w}{N_w}
\]  

(1)

Fig. 3 A Sketch of Jenike Shear Tester.
2.4 Bulk Solids
In this work, soft PE plastic pellets A was used as the tested bulk solids.

2.5 Wall Plates
In this work, 4 different wall surfaces were tested:
1. Stainless Steel SS304 polished
2. Stainless Steel SS304 non-polished
3. Aluminum Al6061 polished
4. Aluminum Al6061 non-polished

The wall roughness, Ra, for each plate has been measured with Surtronic 3+ and shown in Table 2. RST uses a round wall plate and only one orientation’s roughness is measured. However, Jenike shear tester uses a square wall plate. Square wall plates can have different wall roughness in the different orientation due to the manufacturing process. Therefore, the wall roughness on the different orientations (along with grain and against grain) was measured for each square wall plate (apply for Jenike shear tester only).

### Table 1  Finishing process vs approximate range of Ra values

<table>
<thead>
<tr>
<th>Finishing Process</th>
<th>Ra, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-finishing</td>
<td>0.05 – 0.2</td>
</tr>
<tr>
<td>Lapping</td>
<td>0.05 – 0.4</td>
</tr>
<tr>
<td>Diamond turning</td>
<td>0.1 – 0.4</td>
</tr>
<tr>
<td>Honing</td>
<td>0.1 – 0.8</td>
</tr>
<tr>
<td>Grinding</td>
<td>0.1 – 1.6</td>
</tr>
<tr>
<td>Turning</td>
<td>0.4 – 6.3</td>
</tr>
<tr>
<td>Boring</td>
<td>0.4 – 6.3</td>
</tr>
<tr>
<td>Drawing</td>
<td>0.8 – 3.2</td>
</tr>
<tr>
<td>Extruding</td>
<td>0.8 – 3.2</td>
</tr>
<tr>
<td>Milling</td>
<td>0.8 – 6.3</td>
</tr>
<tr>
<td>Extruding</td>
<td>0.8 – 3.2</td>
</tr>
<tr>
<td>Shaping</td>
<td>1.6 – 12.5</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

3.1 Comparisons of Wall Friction Measurement by RST and Jenike Shear Tester

The wall friction angles can be affected by wall surface conditions and bulk solids characteristics. For the purpose of comparing the results of the RST and the Jenike shear tester, only soft plastic pellets A was chosen to be tested by these two methods separately with the same testing conditions besides the wall plates. Here, two wall materials (SS 304 & Al 6061), and two wall surface conditions (polished and non-polished) were tested for the soft plastic PE pellets A. Fig. 4 shows the wall friction angles of soft plastic PE pellets A measured on different SS 304 wall plates with different wall roughness by Jenike shear tester and Schulze ring shear tester. The tests were carried out at 22°C & 37°C, respectively. It can be seen from Fig. 4 (a) and (b) that the wall friction angles are similar if the wall roughness is similar, no matter if the Jenike shear tester was used or Schulze ring shear tester was used.

If the wall roughness is significantly different, Fig. 4 further shows wall friction angles increase with in-

### Table 2  Wall roughness of wall plates

<table>
<thead>
<tr>
<th>Wall Material</th>
<th>Tester/Orientation</th>
<th>Surface Condition</th>
<th>Ra, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 304</td>
<td>Jenike-Against Grain</td>
<td>Non-Polish</td>
<td>1.71</td>
</tr>
<tr>
<td>SS 304</td>
<td>Jenike-Along Grain</td>
<td>Non-Polish</td>
<td>1.45</td>
</tr>
<tr>
<td>SS 304</td>
<td>RST</td>
<td>Non-Polish</td>
<td>1.09</td>
</tr>
<tr>
<td>Al 6061</td>
<td>Jenike-Against Grain</td>
<td>Non-Polish</td>
<td>0.79</td>
</tr>
<tr>
<td>Al 6061</td>
<td>Jenike-Along Grain</td>
<td>Non-Polish</td>
<td>0.57</td>
</tr>
<tr>
<td>Al 6061</td>
<td>RST</td>
<td>Non-Polish</td>
<td>0.36</td>
</tr>
<tr>
<td>SS 304</td>
<td>Jenike-Against Grain</td>
<td>Polish</td>
<td>0.34</td>
</tr>
<tr>
<td>SS 304</td>
<td>Jenike-Along Grain</td>
<td>Polish</td>
<td>0.28</td>
</tr>
<tr>
<td>SS 304</td>
<td>RST</td>
<td>Polish</td>
<td>0.11</td>
</tr>
<tr>
<td>Al 6061</td>
<td>Jenike-Against Grain</td>
<td>Polish</td>
<td>0.50</td>
</tr>
<tr>
<td>Al 6061</td>
<td>Jenike-Along Grain</td>
<td>Polish</td>
<td>0.39</td>
</tr>
<tr>
<td>Al 6061</td>
<td>RST</td>
<td>Polish</td>
<td>0.13</td>
</tr>
</tbody>
</table>
increasing wall roughness independent of wall surface conditions (polished or non-polished) and testing methods (RST or Jenike shear tester). Comparing the wall friction angles in Fig. 4 (a) and (b), it also could be found that wall friction angles have no significant changes under the different testing temperature conditions (22°C and 37°C).

3.2 Wall Friction Angle vs Wall Roughness

Fig. 5 and 6 show wall friction angle vs. wall roughness under 22°C for RST and Jenike shear tester, respectively. It might be concluded from Fig. 5 and 6 that wall roughness of a wall plate is the key parameter to control wall friction angles of soft PE plastic pellets A. The trends in Fig. 5 and 6 predict

![Graph](image1)

**Fig. 4** Wall Friction Angles of Pellets A against Different Surfaces at 22°C & 37°C.
that with increasing wall roughness the wall friction angles increase. It also could be seen from Fig. 5 and 6 that wall friction angles increase with decreasing normal pressure on walls.

Furthermore, it was observed from Fig. 5 and 6 that under high normal pressures (4,600 Pa and 10,000 Pa), wall friction angles only depend on wall roughness, no matter which testing method was used. However, for the low normal pressure (500 Pa), wall friction angles measured by RST are much larger than those measured by Jenike shear tester.

The reason for the difference at low normal pressure is not clear, and also it could not be explained which one is more accurate. However, the low pressure on walls is usually found close to the silo outlet during discharge. If the critical wall friction angle located at the low pressure when designing a silo/hopper, the larger wall friction angle from RST will give

![Image of Fig. 5: Wall Friction Angle vs. Wall Roughness (RST at 22°C).](image)

![Image of Fig. 6: Wall Friction Angle vs. Wall Roughness (Jenike Shear Tester at 22°C).](image)
...more conservative design to avoid the potential of funnel flow. However, a steeper hopper increases total construction cost.

It was derived\(^1\) that an increase in the wall friction angle of \(\varphi_w\) of 1 degree, roughly leads to a decrease in the half hopper angle (measured from the vertical) of 1.3 degree. Therefore, the difference of several degrees of wall friction angles will also significantly impact the evaluation of a silo/hopper for a given bulk solids. The similar relationship of wall friction angle vs. wall roughness was also applied for the higher testing temperature (37°C). The results have been shown in Fig. 7 and 8. By further comparing the curves in Fig. 7 and 8, we can conclude that no significant difference was found between these two testing temperatures.

4. Conclusions

It was found that the most important parameter in this study is wall roughness. With decreasing wall

![Fig. 7 Wall Friction Angle vs. Wall Roughness (RST at 37°C).](image)

![Fig. 8 Wall Friction Angle vs. Wall Roughness (Jenike shear tester at 37°C).](image)
roughness, wall friction angles decrease no matter which tester was used. Wall friction angles for both RST and Jenike shear tester were similar if wall roughness was similar. The only exception is under the testing condition of the low pressure (500 Pa) on a wall plate, while Schulze ring shear tester gave larger wall friction angles than Jenike shear tester did. In addition, wall friction angles have no significant changes under the different testing temperature conditions (22°C and 37°C).

Acknowledgement

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References


Author’s short biography

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Dr. Ting Han received B.S. and M.S. degrees in Metallurgical Science and Engineering from Northeastern University (China). He received Ph.D. degree in Mechanical Engineering from Ben-Gurion University, Israel. He was a postdoc fellow in Chemical Engineering, Carnegie Mellon University, USA. After he joined in the Dow Chemical Company, he worked in solids processing group of Dow Corporation R&D at Freeport, TX for 4 years. Right now he is working in Energy Storage Device Material (ESDM) R&D at Dow Midland, MI, on solids processing, including powder coating, milling and particle characterization.