# A Comparison of Friction Measurements made during Wear on the Linear Abrasive Wear Tester with those on the Jenike Shear Tester

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**Abstract**

Friction measurements were made on two testers: the Jenike shear tester and a linear abrasive wear tester (LAWT). Wall friction values were obtained for a range of steels and surface finishes, typical of the plates used for the manufacture of hoppers and silos in bulk solids handling applications. The abrasive used was crushed soda-lime glass. It was found that friction values on the Jenike were similar to the initial 'start up' values obtained on the LAWT. The latter correlated particularly well with the surface roughness of the sample plates. On the LAWT, friction was found to increase with sliding distance until a steady-state level was attained. It is considered that this increase is due to the gradual accumulation of wear debris, particularly fragmented abrasive particles, on the surface of the wear specimen.

**Keywords:** Three-body abrasion; Friction coefficient; Test equipment

## 1. INTRODUCTION

Surface friction effects at the boundary surface has a profound influence on the design and performance of hoppers, bins, silos, feeders and chutes used in bulk materials handling applications. Of particular significance is the effect of wall friction on the nature of material flow in hoppers, bins and silos, especially under gravity flow conditions. Jenike [1,2] defined the two principal modes of flow as mass-flow and funnel flow (figure 1). In mass flow, the bulk solid is in motion at every point within the hopper whenever material is drawn from the outlet. In funnel flow, the bulk solid sloughs off the top surface and falls through the vertical flow channel that forms above the opening. Although, funnel flow has the advantage of providing wear protection of the hopper walls, the flow pattern is erratic and can lead to segregation problems.

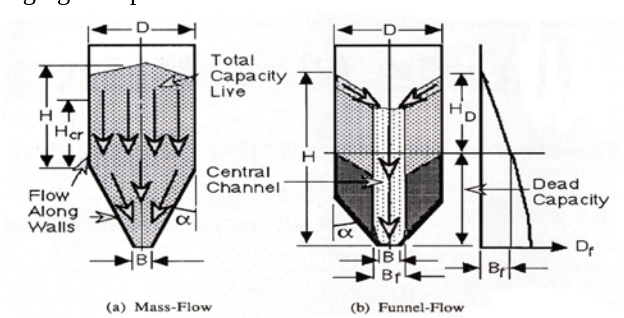


FIGURE 1. Flow patterns in hoppers

For this reason mass flow is usually desirable and hoppers need to be designed accordingly. Mass flow requires steep, smooth hopper surfaces. The appropriate hopper half-angle, $\alpha$, to achieve mass flow (see figure 1) depends on the wall fiction angle, $\phi$, and the effective angle of internal friction, $\delta$. The wall friction angle, $\phi$, is defined as:

$$\phi = \tan^{-1}\left(\frac{\tau}{\sigma}\right) = \tan^{-1}\mu \qquad (1)$$

where $\tau$ is the shear stress at the wall; $\sigma$ is the normal stress at the wall; $\mu$ is the coefficient of friction.

The importance of wall friction angle, $\phi$, on mass flow hopper design is clearly evident. The wall friction angle is generally considered to be dependent on three groups of parameters: bulk solid characteristics (e.g. particle size and distribution, shape, hardness and moisture content); wall surface characteristics (e.g. material hardness and other mechanical properties, roughness, adhesion behaviour); working conditions (e.g. pressure, flow velocity).

In the present study we will be focussing on the effect of wall characteristics and examining the influence of material hardness and surface roughness on wall friction. These are the aspects that the designer and manufacturer of hoppers and silos has most control over. The effect of surface roughness is expected to be most important and has received some attention [e.g. 3-6]. All these studies

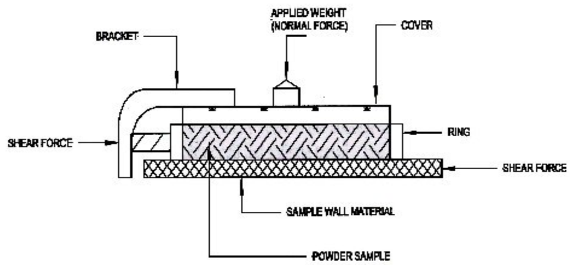


FIGURE 2 . The Jenike shear tester

indicate a relationship between friction, and the relative dimensions of the particles and surface topographical features. There is evidence that with fine particles a 'sticking' layer of powder is formed at the wall, resulting in particle-particle friction effects in addition to particle-wall friction. The amount of reported work in this area is relatively limited however and our understanding of the effect of surface roughness on friction by no means complete. The present study will examine particle-surface interactions for a number of steels with different hardness values and a range of surface finishes, and using large abrasive particles where abrasive wear is expected to be pronounced.

The wall friction of a wall material-bulk solid combination is generally measured using a Jenike shear tester [2]. This is illustrated in figure 2. The Jenike shear tester has been the subject of several international standards, including ASTM Standard D6128. Few direct measurements of wall friction in hoppers have been obtained. However, experience has shown that Jenike type shear tests can lead to conservative values of the measured friction angles [3]. In response to this perceived problem, a new type of friction tester/linear abrasive wear tester was developed jointly by the Universities of Twente (Netherlands) and Newcastle (Australia) [7], which, it was argued, would allow friction values to be measured under conditions more similar to those operating in industrial plant.

In the present work, friction measurements on a linear abrasive wear tester (based on the aforementioned design [7]) were compared with those made on a Jenike shear tester for a number of different steels with a range of surface finishes, and with a bulk solid of large abrasive particles. The work was carried out in order to assess the suitability of the Jenike shear tester as a means of measuring wall friction for use in the design of hoppers and silos for handling abrasive particles. The materials and surface finishes chosen were therefore compatible with these aims in that both were typical of those used in the bulk solids handling industry.

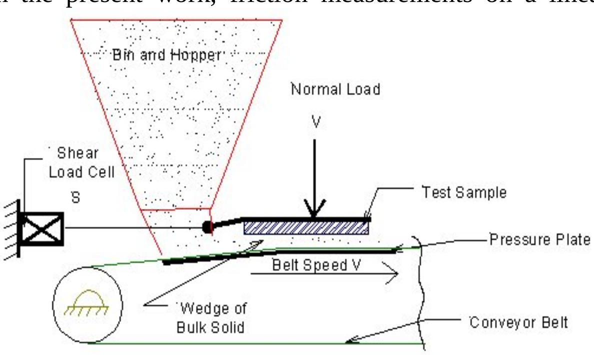


FIGURE 3. Linear Abrasive Wear Tester (LAWT)

## 2. EXPERIMENTAL

### 2.1 Friction measurements

Friction measurements were made on both the Jenike shear tester (figure 2) and the linear abrasive wear tester, LAWT (figure 3). In the Jenike tester, a stiff metal ring of diameter 95.25mm, and vertically loaded by a dead weight encloses a relevant sample of the bulk solid. The bulk solid is then sheared over a steady sample plate and the shear load is measured at constant sliding speed for a sliding distance of around 10mm. The shear load is measured as a function of a series of decreasing loads. In the present work the normal load was reduced from 10 kg to 0 in 1 kg steps. A plot of shear stress against normal stress gives points on the so-called 'wall yield locus' from which the wall friction angle may be determined.

The LAWT (figure 3) attempts to simulate more closely the conditions experienced in practice during bulk solid handling applications. Key to the operation of the tester, and the simulation of hopper and silo operating conditions, is the establishment of a bed of particulate matter beneath the sample plate. In the present work this bed was around 4-5 particle diameters in thickness. The bed of particles is achieved by means of a wedge of material at the leading edge of the specimen. The formation of a bed of bulk solid beneath the specimen would suggest that conditions of 3-body wear operate in which rotation of particles occurs.

### 2.2 Materials and initial experimental investigation

Five steel alloys were chosen for the experimental programme, all of which are commonly used as wall materials in hoppers and silos. The five materials and their nominal compositions (weight %) are:
EN 43A STEEL: 0.5 C ; 0.85 Mn ;
304 STAINLESS STEEL: 18 Cr ; 10 Ni
CROMWELD 3CR12: 12 Cr ; 0.5 Ni
ABRO 400: 0.14 C ; 1.6 Mn ; 0.3 Cr ; 0.25 Ni ; 0.25 Mo
HYFLOW 420R: 13Cr

TABLE 1. Experimental Materials

| Sample Plate | Surface Finish | Sample Code | Vickers Hardness (HV) |
|---|---|---|---|
| En 43A Steel | With Mill Scale | 43A (Mill) | 165 |
| En 43A Steel | 400 Grit finish | 43A (400Gr) | 165 |
| En 43A Steel | 800 Grit finish | 43A (800Gr) | 165 |
| 304 Stainless Steel | No. 1 finish (Hot Rolled + Descaled) | SS 304 (No1) | 209 |
| 304 Stainless Steel | 2B finish (Cold Rolled) | SS 304 (2B) | 177 |
| 304 Stainless Steel | 180 Grit finish | SS 304 (180Gr) | 209 |
| Cromweld 3CR12 | No. 1 finish (Hot Rolled + Descaled) | 3CR12 (No1) | 163 |
| Cromweld 3CR12 | 2B finish (Cold Rolled) | 3CR12 (2B) | 163 |
| Cromweld 3CR12 | Bunker finish (Ra 1 µm) | 3CR12 (1 µm) | 163 |
| Cromweld 3CR12 | Bunker finish (Ra 0.5 µm) | 3CR12 (0.5 µm) | 163 |
| Abro 400 | With Mill Scale | Abro (Mill) | 415 |
| Abro 400 | 800 Grit Finish | Abro (800Gr) | 415 |
| Hyflow420R | With Mill Scale | Hyflow (Mill) | 425 |
| Hyflow420R | 800 Grit Finish | Hyflow (800Gr) | 425 |

En 43A is a ferrite/pearlite medium carbon steel; 304 is an austenitic stainless steel; Cromweld 3CR12 is a duplex ferritic-martensitic stainless steel; Hyflow 420R is an 'as quenched' martensitic stainless steel; Abro 400 is a heat-treated alloy steel.

Each of these steels was supplied in various forms with different surface finishes depending on the prior processing they had undergone. The materials and their as-received surface finish are listed in Table 1. Also given is the measured Vickers hardness value of the plate and a sample code used in this paper as a convenient shorthand means of identification. In friction/wear tests it is normal to polish all specimens to a common smooth finish. However, in the present study, to do so would contradict the aims and objectives of the work, namely to examine the friction characteristics of materials and finishes used as wall materials in hoppers and silos. Therefore the initial experimental investigation examined the materials in the as-received conditions. The objective of the initial test programme was to compare the wall friction angle (expression (1)) obtained using the Jenike shear tester and the LAWT. The test materials were supplied in plate form and specimens were cut from them. The specimens were of dimensions 150mm length x 100mm width, which allowed them to be used on both the LAWT and Jenike testers. The plate materials were always cut such that the length was in the polishing or rolling direction. Friction measurements on the LAWT and Jenike testers were made in the length direction. This was considered to be representative of bulk solid flow in industrial plant.

The abrasive material (sample bulk solid) chosen for the test programme was crushed soda-lime glass of mean particle size 300µm, supplied by Vacu-Blast Ltd., Slough, UK. SEM examination revealed that the particles were generally of sharp angularity, although occasionally rounded ones were observed that had survived the crushing process. This abrasive material was used for measuring the frictional interaction with the plate materials on both the LAWT and Jenike testers.

The test procedure adopted for the initial test programme is summarised below:

i. The sample was ultrasonically cleaned in Iso-Propyl Alcohol (IPA) and its mass measured.
ii. Surface texture measurements (Ra and Sm) were made along and across the polishing/rolling direction on the cleaned sample plate.
iii. The wall friction of the cleaned sample plate was measured on the Jenike shear tester.
iv. The as-received/un-worn sample plate was mounted on the LAWT under a dead weight of 8.8 kg and the shear force monitored for the duration of a 30 minute wear run.
v. The worn sample plate was ultrasonically cleaned in IPA and its mass measured.
vi. Surface texture measurements (Ra and Sm) were made along and across the polishing and rolling direction on the cleaned, worn sample plate.
vii. The wall friction of the ultrasonically-cleaned, worn sample plate was measured on the Jenike shear tester.

Mass measurements were required for a parallel study of wear on the LAWT. The wear results are not reported in this paper. Surface texture measurements were made using a Taylor-Hobson Surtronic 3+ profilometer. Surface texture was characterised using Ra and Sm values. The Ra value is a height parameter commonly known as the centre-line average roughness. The Sm value is the average peak-to-peak spacing of the measured profile. The belt speed selected for the LAWT was 0.183 m/s. The duration of the test run (30 minutes) therefore gave a total 'sliding' distance of 329.4m. The nominal applied stress on the test sample was 5.75 kPa, considered to be representative of operating conditions in a hopper.

### 2.2 Further work- Investigation of measured differences between friction on the LAWT and Jenike testers.

As a consequence of results obtained from the initial experimental investigation, a second investigation was carried out. The aim of this second investigation was to measure the wall friction on the Jenike shear tester under conditions more closely resembling those on the LAWT. It was considered possible that ultrasonic cleaning of the sample plates before testing on the Jenike might affect the wall friction values obtained. It was desired that the sample plates be removed from the LAWT and placed directly in the Jenike tester. This proved to be impossible, however, as extraneous loose particulate matter on the sample plate prevented the containing ring for the bulk solid being laid flat. Instead the sample was given a perfunctory clean with a compressed air-blast to remove any loosely attached matter before being placed on the Jenike rig. The selected sample plates were cut to size and prepared by grinding flat before polishing by standard metallographic techniques to the indicated finishes. Polishing was along the length of the sample plate as were subsequent friction measurements on the LAWT and Jenike testers. The test procedure for this second investigation was only slightly different to that of the initial investigation. The difference was that in this second test the sample plate was removed from the LAWT (after a 30 minute wear run) and de-dusted using compressed air. A friction measurement was then taken on the Jenike tester. Subsequently, the sample was further cleaned ultrasonically in a bath of IPA and a final Jenike friction measurement taken.

A further investigation involved an examination of the possible effect of the ultrasonic cleaning solution on subsequent LAWT and Jenike friction measurements. Friction measurements on samples, after ultrasonic cleaning in IPA and distilled water, were compared. SEM examination of wear surfaces was also carried out. This was not straightforward as the sample plates were too large to fit directly into the SEM. The sample plates therefore required sectioning. It was desirable that the specimens were handled carefully during this operation, that the surface was undisturbed, and that extraneous matter was not introduced onto the surface. No available cutting operation was without flaws, but it was decided to guillotine the samples to the necessary size.

## 3 RESULTS

### 3.1 Initial experimental investigation

Table 2 shows surface texture measurements made on the plates before and after the 30 minute wear run. Surface texture (Ra and Sm) values are given both along and across the direction of polish/rolling on the as-received sample plates. The polish/rolling direction was also chosen as the abrasive wear sliding direction and the shear direction for friction measurements. That is to say, friction and wear measurements were measured parallel to the surface roughness features of the sample plate.

Table 2 generally indicates a gradual smoothing of the plate surface (i.e. a reduction in Ra and an increase in Sm) during the 30 minute wear run. The main exceptions to this are the sample plates with heavy ‘mill scale’ (ABRO(MILL) and HYFLOW(MILL)). Both of these plates had surfaces with thick oxide films, such that in the relatively short 30 minute wear run, most (if not all) of the mass loss recorded was due to the removal of this oxide. This occurred with little change to the surface finish. Another exception was 304 stainless steel (No1 Finish) whose surface was substantially covered in an oxide film. This material, although exhibiting significant wear as indicated by mass loss measurements, also showed little change in surface roughness.

Table 3 indicates the friction measurements made during wear testing on the LAWT and the comparative measurements made (on the same samples) on the Jenike shear tester. The friction measurements in Table 3 are given as wall friction angles. These were calculated using expression (1). Data obtained from the Jenike tester was used to plot shear stress against normal stress, which for all specimens had the form of a straight line through the origin. This is a typical relationship for a non-adhesive material and would be expected of the crushed soda-lime glass used in the present investigation. The wall friction angle may therefore be found from the slope of the graph.

Figure 4 gives selected examples, for a number of the sample plates, of the wall friction data that was obtained from the LAWT. Different plate materials exhibited significantly different behaviour. Materials with heavy ‘mill scale’ or surface oxides layers, e.g. ABRO(MILL), HYFLOW(MILL) and 3CR12(No1), displayed constant wall friction angles throughout the duration of the wear run. These values were generally close to those measured on the Jenike tester (see Table 3) both before and after the ‘wear’ run. Other materials, when tested on the LAWT, had relatively low initial start-up values which were generally close to the Jenike test values of the as-received unworn plates (see Table 3). However, for these materials, during the early stages of wear (usually the first 400 seconds) the friction value as measured on the LAWT increased dramatically (by 100-200%) until it attained an effectively steady-state plateau level far higher than the initial value measured on the Jenike tester. Interestingly, Jenike friction measurements made on ultrasonically cleaned sample plates after the wear run again indicated low wall friction values comparable to the initial values.

If the friction values (Table 3) are compared to the surface texture values (Table 2) some discernible, if not always consistent, trends are apparent. In some cases the effects of surface roughness may be obscured by the influence on friction of surface oxide scales. The clearest relationship

TABLE 2. Surface texture measurements

| Sample Code | Ra Values (µm) | | | | Sm Values (µm) | | | |
|---|---|---|---|---|---|---|---|---|
| | Across "Un-Worn" Surface | Across Worn Surface | Along "Un-Worn" Surface | Along Worn Surface | Across "Un-Worn" Surface | Across Worn Surface | Along "Un-Worn" Surface | Along Worn Surface |
| 43A (Mill) | 0.68 | 0.65 | 0.66 | 0.66 | 140 | 138 | 118 | 120 |
| 43A (400Gr) | 0.10 | | 0.10 | | 72 | | 303 | |
| 43A (800Gr) | 0.33 | 0.092 | 0.16 | 0.10 | 214 | 217 | 63 | 112 |
| SS 304 (No1) | 4.56 | 5.00 | 4.86 | 4.78 | 121 | 116 | 137 | 123 |
| SS 304 (2B) | 0.27 | 0.18 | 0.30 | 0.18 | 33 | 131 | 32 | 283 |
| SS 304 (180Gr) | 2.30 | 1.78 | 0.98 | 0.42 | 61 | 130 | 194 | 387 |
| 3CR12 (No1) | 4.76 | 3.84 | 4.21 | 2.99 | 154 | 301 | 149 | 373 |
| 3CR12 (2B) | 0.16 | 0.16 | 0.31 | 0.15 | 59 | 102 | 137 | 230 |
| 3CR12 (1 µm) | 0.84 | 0.60 | 0.42 | 0.28 | 49 | 106 | 329 | 300 |
| 3CR12 (0.5 µm) | 0.32 | 0.34 | 0.15 | 0.20 | 49 | 83 | 378 | 189 |
| Abro (Mill) | 3.98 | 3.95 | 3.48 | 3.50 | 186 | 185 | 137 | 136 |
| Abro (800Gr) | 0.06 | 0.06 | 0.06 | 0.05 | 512 | 311 | 214 | 339 |
| Hyflow (Mill) | 1.52 | 1.50 | 3.12 | 3.14 | 146 | 143 | 156 | 158 |
| Hyflow (800Gr) | .05 | .04 | .05 | .08 | 380 | 337 | 329 | 413 |

is between the surface roughness parameter Ra (measured either across or along the surface roughness features) and the initial 'start-up' friction value on the LAWT. Figure 5 shows the relationship between LAWT 'start-up' friction and Ra (measured across). It should be noted that despite the similarity of LAWT 'start-up' and initial Jenike test values, the same trend is not as consistent using Jenike friction values. It is also clear that the LAWT 'steady-state' wall friction value is relatively insensitive to surface roughness.

TABLE 3. Measured wall friction values

| Sample Code | Wall Friction (Degrees) | | | | LAWT Time to Steady State (Seconds) |
|---|---|---|---|---|---|
| | Jenike As Received | Jenike Worn Sample | LAWT Initial | LAWT Steady State | |
| 43A (Mill) | 15.1 | 15.0 | 17.3 | 23.6 | 70 |
| 43A (400Gr) | 20.6 | 11 | 12.9 | 26.8 | 180 |
| 43A (800Gr) | 9.1 | 9.2 | 8.5 | 25.5 | 200 |
| SS 304 (No1) | 28.4 | 32.3 | 19.9 | 30.5 | 400 |
| SS 304 (2B) | 12.1 | 8.7 | 9.44 | 26.8 | 300 |
| SS 304 (180Gr) | 10.2 | 9.5 | 25.5 | 30.3 | 130 |
| 3CR12 (No1) | 29.7 | 24.0 | 27.0 | 26.8 | 0 |
| 3CR12 (2B) | 14.4 | 10.2 | 9.9 | 25.0 | 200 |
| 3CR12 (1 µm) | 10.2 | 11.8 | 13.6 | 28.1 | 400 |
| 3CR12 (0.5 µm) | 8.4 | 10.6 | 8.0 | 26.3 | 130 |
| Abro (Mill) | 27.3 | 31.7 | 29.9 | 29.5 | 0 |
| Abro (800Gr) | 15.7 | 6.9 | 13.5 | 31.6 | 80 |
| Hyflow (Mill) | 25.6 | 31.7 | 27.5 | 27.3 | 0 |
| Hyflow (800Gr) | | | 8.5 | 28.6 | |

For a given material, friction values are generally similar. In addition, wall friction values are clearly independent of hardness.

### 3.2 Further work- Friction differences between LAWT and Jenike testers

The difference between the steady state LAWT wall friction value and that of the ultrasonically cleaned plate Jenike values was commented on earlier. An attempt was therefore made to attain Jenike values with the surface of the sample plate in a condition as close as possible to that attained on the LAWT tester. Jenike values were therefore also obtained for sample plates that after removing from the rig were de-dusted using low pressure compressed air. Results are given in Table 4. It is apparent that the Jenike wall friction values of the de-

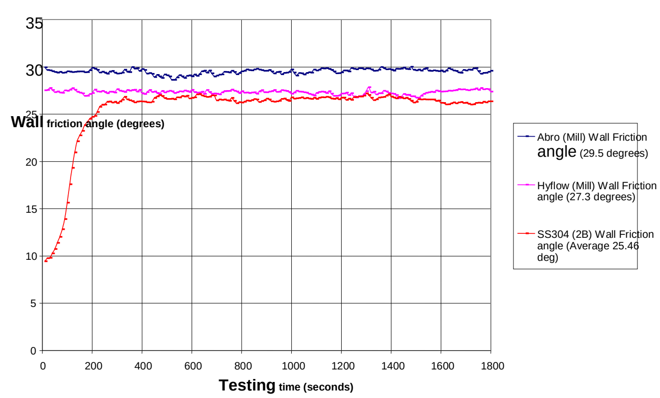


FIGURE 4. Wall friction against wear test run-time

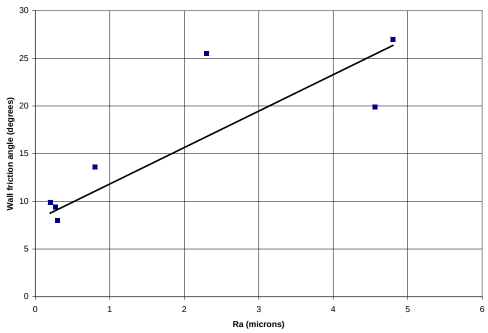


FIGURE 5. LAWT start-up friction value against Ra (across)

dusted plates are intermediate between the LAWT steady-state and the Jenike ultrasonically cleaned sample values.

In another experiment, the potential effect of the ultrasonic cleaning solution was examined. Jenike friction values on worn plates were compared after ultrasonic cleaning in IPA (the standard solution used in the present work) and distilled water. A negligible difference resulted from these two cleaning processes, and it may be concluded that the friction results obtained are a result of ultrasonic cleaning and not the cleaning solution.

## 4 DISCUSSION

The results obtained need to be discussed within the context of the stated aims and objectives of the work. The present results provided no evidence that hardness affected friction values. It is not generally expected that hardness will influence friction. A classical treatment of friction shows no affect of hardness on either the adhesive or deformation friction forces. However, Bradley et al [8] pointed out that hardness could have an indirect affect by controlling the penetration depth of a particle for a given load. For 'blunt' particles, this may consequently affect the 'attack angle' of the particle and hence the friction. There was however a clear indication (figure 5) that surface roughness does influence wall friction as indicated by LAWT initial 'start up' values. Consistency of results in this respect was however adversely affected by other factors, notably the presence of surface oxide. Previous work [3-6] has also indicated a relationship between surface friction and roughness for interactions between bulk solids and sample plate materials. In the system studied here, it is expected that the friction force will result from deformation of the surface by the particle asperities. The adhesion friction force is expected to be negligible. Classical models of friction consider interactions between hard asperities and flat surfaces. The presence of a surface texture may act in a number of

TABLE 4. Wall friction values (degrees)

| Sample Code | Lawt Steady State | Jenike De-Dusted Sample | Jenike Ultrasonic Clean Sample) |
|---|---|---|---|
| 43A (400Gr) | 26.6 | 17 | 11.0 |
| 43A (800Gr) | 25.2 | 16.2 | 9.2 |
| 3CR12 (0.5 μm) | 27.3 | 24.2 | 10.2 |
| Abro (800Gr) | 28.5 | 19.9 | 7.5 |
| Hyflow (800Gr) | 27.6 | 16.3 | 9.9 |

ways. Firstly, an increase in surface roughness would be expected to increase friction through an increase in the number of particle-surface contacts and the effective contact length per unit sliding distance. Additionally, the surface plastic strain will perhaps be increased by such interactions. Greater surface roughness may also lead to higher friction through an increase in the effective attack angle of the particles.

Comparison of the friction measurements made on the LAWT and Jenike testers indicated startling, previously unreported, differences. Previous comparisons have been made between the two testers. Roberts et al [5] compared the two for bauxite sliding on Bisalloy 500. Marginally lower friction values were obtained on the LAWT, which was attributed to the higher relative sliding velocity employed on the tester. Further tests showed similar results. The present results (Table 4) showed no conclusive trend in this respect. Results show similarities between the initial start-up friction values on the LAWT and those obtained on the Jenike. Of more significance, the present study shows that for most of the samples tested on the LAWT, the wall friction value rises dramatically from this initial value until a 'steady state' plateau is attained. This generally occurs within the first 400 seconds, equivalent to a sliding distance of around 73m. This steady state friction value is significantly different to both the LAWT start-up value and that of the Jenike. Such behaviour has not been reported previously.

To understand the origin of this increase in friction, the physical processes occurring during the early stages of the wear run must be considered. The magnitude of the friction values indicate the wear and friction mechanisms in operation. The range of measured wall friction angles observed in the test work was from 8.4º, on the Jenike, to a steady–state LAWT level of 31.6º. Expression (1) indicates that the corresponding range of coefficient of friction values,μ, is 0.51 to 0.61. The Jenike and LAWT 'start up' values are indicative of 3-body abrasive wear conditions in which particles are free to rotate. This might be expected of a deep bed of particles and was one

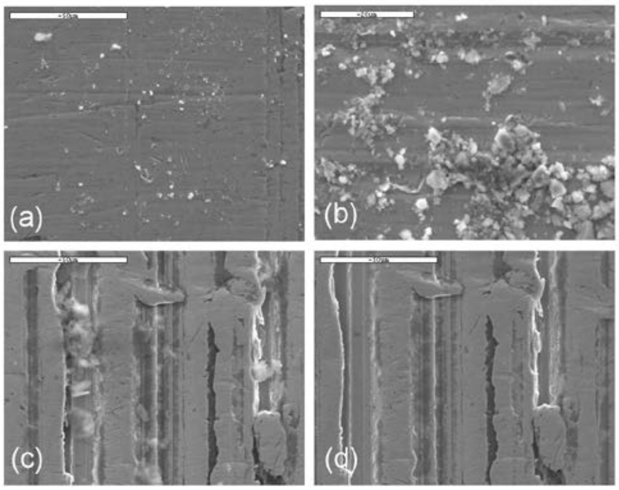


FIGURE 6. SEM pictures of wear surfaces showing wear debris

of the key features in the design of the LAWT. The higher steady state LAWT friction values cannot preclude the possibility of 2-body abrasive wear. Zum-Gahr [9] reported friction coefficients from 0.5 to 0.8 for austenitic steel and tool steel in 2-body abrasion in which grooving wear definitely occurred. The possibility that ‘bedding in’ of the particles occurred at the start of the wear run, causing the particles to become locked in position, was considered. Such a process might lead to a change in the mode of particle movement across the specimen surface from rolling to sliding and grooving, and result in an increase in friction. However, this possibility is easily dismissed by the realisation that ‘bedding-in’ must occur within the time that it takes a particle to traverse the length of the sample plate. The time interval before steady state friction is achieved (Table 3) is several orders of magnitude too high to be explained by a bedding-in process.

The length of the time interval suggests that the increase in friction on the LAWT during the early stages of the wear run, can only be explained by the nature of the changes occurring at and to the surface of the sample plate. As the wear run proceeds a number of changes will occur. Contact between the particles and the surface asperities will tend to smooth out the surface. The change in the measured surface texture parameters between the un-worn and worn surfaces (Table 2) confirms that this generally occurs. However, it has previously been concluded that a reduction in surface roughness leads to a decrease in friction (figure 5). Plastic deformation of the sub-surface will also occur as a result of the particle-asperity contacts. This in most cases will lead through work hardening to an increase in surface hardness. However, it has already been stated that friction appears to be independent of hardness. Moreover, the results of the present study indicate that such changes do not affect the subsequent Jenike friction values. The worn plate Jenike values are much the same as that of the unworn plate. Furthermore, in staggered wear tests, in which a worn plate is removed from the LAWT and ultrasonically cleaned before replacing on the rig, a time interval was required before steady state values were once more attained.

It would appear that the only possible explanation for the increase in friction is an accumulation of wear debris on the wear surface. This is possible on the LAWT but not the Jenike because of the much longer sliding distance on the former. The sliding distance on the Jenike is only 10mm. The time to reach the steady state friction value on the LAWT is between 70 and 400 seconds (equivalent to sliding distances of 13-73m). SEM examination of the sample wear surface showed that much of the wear debris present consisted of fragments of glass particles typically 0.5 to 5μm in size (figure 6). Metallic wear debris was less in evidence although agglomerations of oxide plates were noted, similar to wear debris typically observed after sliding wear. The wear debris present was relatively strongly attached to the surface and was not detached by a short low-pressure air-blast. However ultrasonic cleaning was shown to be capable of removing debris (compare figures 6(c) and (d)). Clearly, this may explain the reduction in friction observed on the Jenike after ultrasonic cleaning. The amount of wear debris observed was perhaps less than might be considered necessary to significantly raise friction, but it was considered that a large proportion of the debris might well have been removed during the guillotining of the large sample plates, necessary to allow SEM examination.

There is significant evidence that wear debris can affect friction. Zhang et al [10] developed a detailed friction model for dry sliding metal contacts, which included the contribution of metallic wear debris, and Sherrington and Hayhurst [11] assessed the model experimentally. They found that generally friction increases as sliding distance and the density of wear debris increased. Whether this is relevant to wear by abrasive particles is perhaps debatable, although it is possible that adherence could occur between the particles and the debris.

More pertinent perhaps is a study by Yao and Page [12] on friction measurement on Ni-Hard 4 during high pressure crushing of silica. Although, the normal stresses employed in this study were several orders of magnitude greater than those employed in the present work, it is interesting to note that they also observed an increase in friction with sliding distance until a plateau value was attained. The plateau value coincided with the development of a layer of fine powder at the specimen surface. Moreover, although the stresses used by Yao and Page were much higher, their sliding distances were much shorter (15mm compared to 329.4 m in the present work). It seems possible that in the present work, the highly brittle soda-lime glass could undergo fragmentation. Soda-lime glass has a fracture toughness around 1 MPa√m.

Dube and Hutchings [13] examined the fracture of silica sand abrasive particles in the low and high stress abrasive wear of steel and found that fracture of the abrasive particles occurred over a wide range of test conditions, including loads similar to those of the present work. The present experimental rig made examination of particle fracture difficult, as the abrasive was re-circulated. Evidence suggested that particle fracture was not extensive and particles collected for examination before and after the sample plate showed little difference. It may be that heavy fragmentation of particles does not occur in the present work. However, chipping and micro-scale fragmentation of load bearing asperities might be sufficient to cover the wear surface in a fine abrasive dust after the passage of a large number of particles, resulting in the observed increase in friction. Dube and Hutchings [13] showed an increase in friction with load where more extensive fragmentation occurred. Roberts et al [7] demonstrated a threefold increase in friction for coal against polished mild steel after the coal particles were allowed to bond and adhere to the steel during undisturbed storage. Strijbos [6] also suggested that particle-particle contact was responsible for high friction. In the present work, it was also summised that friction was raised by the presence of fine glass fragments on the wear surface resulting in extensive particle-particle contact.

In the present work it is notable that the highest Jenike and LAWT start-up friction values are found for materials with extensive surface oxides which will interact in a similar manner to particle-particle contacts. Furthermore, the LAWT friction values for materials with surface oxides remain constant throughout the wear run. The two materials with particularly heavy surface oxides, ABRO(MILL) and HYFLOW(MILL) had loosely adhered oxide films that in the case of HYFLOW(MILL), in particular, could be removed as a fine red/brown powder by rubbing with a fingertip. The large mass losses recorded during the wear runs for these two materials were due to the removal of these oxides. It is unlikely that any fragmented glass particles, if indeed fragmentation occurred in this instance, would adhere to the surface and further influence friction.

## 5. CONCLUSION

The aims of the work presented in this paper were essentially twofold. Firstly, to assess the effect of wall hardness and surface roughness on the friction characteristics of the wall material. Secondly, to compare the friction values obtained from two different types of tester (the LAWT and the Jenike shear tester) and to evaluate the suitability of both for use in the design of hoppers and silos.

The present work indicated that of the two wall friction characteristics, only surface roughness had any effect on friction. The two testers were found to give different values of wall friction for the particular wall material – abrasive particle interactions studied. The steady-state friction value obtained on the LAWT might be expected to correspond closely to that at a hopper wall during operation, as the tester running conditions were chosen for just this reason. Therefore, although the Jenike shear tester is used internationally in hopper design, the suitability of its use when hard, brittle abrasive materials are to be conveyed is made questionable by the findings of the present work.

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