Published paper
Camacho, J., Lewis, R. and Dwyer-Joyce, R.S. (2007) *Wear of a chute in a rice sorting machine,* Wear, Volume 263 (1 - 6), 65 - 73.

WEAR OF A CHUTE IN A RICE SORTING MACHINE

J. CAMACHO, R. LEWIS*, R.S. DWYER-JOYCE

Department of Mechanical Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD

*Corresponding author

ABSTRACT

In a rice sorting machine, rice grains drop onto and slide down an anodised aluminium chute. The purpose of the chute is to separate the grains and provide a controlled distribution. At the bottom of the chute the grains are examined optically and contaminants or defective grains are removed from the stream by jets of air. The machine has the ability to sort low quality rice which contains a large element of contaminants such as husk. The husk is extremely abrasive and this, along with other factors, can lead to a reduction in the life of the chute by wear of the surface.

In this work a failure analysis process was undertaken to establish the nature and causes of the chute surface wear and the mechanisms of material removal. Wear occurs initially at the location where the grains first strike the chute and at subsequent regions down the chute where bounce occurs.

An experimental and analytical examination of the rice motion on impacting the chute was also carried out along with some friction testing of potential replacement chute materials.

The evidence gathered during the failure analysis along with the experimental analysis was used to propose possible material/design improvements.

Keywords: Rice chute, failure analysis, abrasive wear, erosive wear

1 INTRODUCTION

Food sorting or processing equipment is susceptible to most types of wear, although due to the nature of the products, for example sugar, rice grains, corn etc., which are small particles, the wear is usually abrasive or erosive in nature. Very little work has been published in this area, however, and most seems to focus on wear of sugar processing equipment [1, 2].

The case study presented here is on a chute from a rice sorting machine, which is illustrated schematically in Figure 1. Rice enters the machine through the input hopper and is vibrated towards the anodised aluminium chute along a tray. The rice drops off the edge of the tray onto the chute and slides down. The chute has the effect of separating the grains so they arrive at the end in a continuous stream. At the end of the chute there is a detector head consisting of a number of cameras. An image is taken of each grain as it passes the head. The image is quickly processed and compared to a reference standard that is used to accept or reject the grain. A series of air jets controlled by high speed poppet valves are used to blow the defective grains or contaminants out of the stream

The machine is very effective at rapidly sorting rice and other granular foodstuffs. The process can be used to sort lower quality and dirtier rice to remove husk and contaminating particles. Using the machines for increasingly dirty product has meant that greater wear has occurred as this type of rice has a large element of husk present and other contaminants which are highly abrasive.

The aim of this work was to examine a worn chute to establish what type of wear mechanisms occur. A series of material surface treatments were evaluated for friction and wear performance as possible replacements for the chute surface. In addition, a high speed video technique was used to examine the behaviour of individual rice grains as they impact the chute. The intention was to use this information to propose possible design improvements to the chute to reduce wear problems and increase the life of the chute.

2 CHUTE ANALYSIS

Figure 2 shows a simplified schematic diagram of the chute that was analysed. The chute is 1m long and 0.3m wide and is positioned at an angle of 60° in the sorting machine. This means that the rice impacts the chute at an angle of 30°. The rice drops a distance of 30mm on to the chute. The chute has a number of separating ridges going from top to bottom, which form 0.01m wide channels for the rice grains to slide along. The positions of the wear scars observed are indicated.

At the top of the chute there is a line of fairly uniform wear scars on both the ridges and the channels (see Figure 3a). The anodised surface has been worn away to expose the aluminium substrate.

The wear scars towards the bottom of the chute were seen to be in random positions (see Figure 3b), the reason for this was not initially clear. Again at these points the anodised layer was worn right through to the underlying aluminium.

Figure 4 is a micrograph taken at point A on Figure 2. This shows the appearance of the unworn anodised surface, to allow comparison with the subsequent images of worn regions of the chute. Note all photographs are orientated parallel with the groove direction.

The wear scar at point C on the chute is approximately elliptical in shape (as shown in Figure 3). Figure 5 shows microscopy images of the top and bottom parts of this scar. In Figure 5a, the top of the wear scar, the surface is clearly indented as a result of the impacting rice grains. Similar features were evident on the top of the ridges (point B). At the bottom of the wear scar, however, the surface features have changed to extended scratches, typical of abrasive wear. The dashed lines indicate the extent of the exposed aluminium.

Figure 6 shows the surface in one of the wear tracks seen at the base of the channels (point D). Clearly here the anodised surface has not been completely worn through. There are some linear features just about visible.

Figure 7 shows the top and bottom of one of the randomly positioned wear scars near the end of the chute (point E). Overall the wear is less severe than in the scars at the top of the chute. At the top there is a small amount of pitting, but the scar is mainly made up of parallel scratches.

The evidence of the wear scars suggests the following process is taking place. Initially the rice impacts the rice chute causing indents where it first strikes the chute (the top wear scar). It still must have a relatively high kinetic energy and causes abrasive scratches in the region close to the impact point. The rice then slides down the channels at a lower velocity. The wear is less severe here and does not wear through the anodising. However, there are locations where the grains bounce. It is not clear what causes these, possibly some initial defect on the chute surface that is subsequently magnified by localised wear. The bounce causes re-impacting of the rice grains and further wear scars.

3 MATERIALS TESTING

A number of surface treatment techniques were chosen for testing to assess their suitability for use on the rice chute to help reduce the wear problem. These were hard anodising alone, hard anodising incorporating PTFE, and chrome plating. Untreated aluminium was also tested. Details of the treatments and resulting surface roughness and hardness are given in Table 1.

The Vicker’s micro-hardness of individual rice grains was also measured (using 100g) and found to be between 20-29Hv.

3.1 Friction Testing

A sliding friction test apparatus (based on a Bowden and Leben type machine [3]), shown schematically in Figure 8, was used for the friction tests. The top specimen is attached to a loading arm that is free to move. Dead weights are applied to the loading arm. The counterface specimen is attached to the moving bed, which is driven at constant velocity by a motor and worm drive. As the motion starts the top specimen is moved by the frictional force such that the loading arm contacts a force transducer. The dead weight load on the arm is known, so the friction coefficient can be determined from the measured friction force.

For these tests rice grains were attached to the top specimen as shown in Figure 8. Three were attached in parallel and were pointed lengthways in the direction of motion. Careful checks were made to ensure all three grains were contacting the counterface.

Loads of 40N and 60N were used and a sliding speed of 1.5mm/s. These were selected to ensure that a good stable test could be performed and were not intended to replicate the actual situation, where the loads are much lower and the speeds higher. Tests were performed initially on uncleaned surfaces (surfaces used in as received condition – while this was uncontrolled it was an attempt to replicate the chute conditions in the chute where the chute would not be cleaned) and then on ethanol cleaned surfaces. Runs were repeated 10 times.

Average results for the tests are shown in Figures 9a and 9b. As can be seen there is little difference between the friction coefficients between the two loads for cleaned surfaces, there is a slight reduction for unclean surfaces for 60N. The presence of PTFE in the anodising process did not appear to reduce the friction coefficient. The presence of rice dust on unclean surfaces probably acts to reduce the friction slightly by providing a separating layer. The aluminium surface is somewhat smoother than the others. The asperities on the rough surfaces will cut into the softer rice grains leading to a higher deformation component of friction. The unclean aluminium a 40N gives an exceptionally low value. Possibly at this lower load the rice dust provides a more effective layer separating the grains from the smoother counterface.

3.2 Wear Testing

Wear tests were carried out on small sections of the different chute material treatments using a high frequency reciprocating rig, as shown in Figure 10. An electrical oscillator is used to reciprocate the test head at high frequency. A dead weight is applied directly to the test head (in this case 120g). The electrical oscillator was driven using a sine-wave generator to produce a reciprocating frequency of 150Hz and a stroke length of 5mm. One grain of rice was bonded onto the upper specimen. A single grain was used to increase the contact pressure and accelerate wear. The wear was assessed purely by inspection of the wear scars. Mass losses were two small to be weighed directly.

Tests were carried out using just rice and with the addition of an abrasive to simulate the effect of having husk present in the rice (0.03g of 0-1μm SiC was added to the contact area prior to lowering the rice grain to the counterface and starting the electrical oscillator).

Figure 11 shows the material surfaces before and after testing with just rice. The untreated aluminium suffered the most severe wear. Aluminium wear debris was found to be picked up and adhered onto the rice grain. This lead to an acceleration of the two-body abrasive wear process.

The treatment that saw the greatest wear was hard anodising with PTFE. In Figure 11b it can be clearly seen that the surface layer has been worn more severely than the other surfaces. Linear scratches in the direction of rice motion are visible indicating that abrasive wear is again occurring on the substrate. Features were similar to those seen on the actual rice chute wear scars. The chrome plated and hard anodised aluminium showed less wear. After 30 minutes the coatings were largely intact (see Figure 11c and 11d).

Tests carried out with the addition of SiC particles lead to far more severe wear as can be seen in Figure 12. Wear volume data (shown in Figure 13), calculated using profilometer traces of the wear scars, shows that with the abrasive particles wear increased by an order of magnitude. The wear data backed up the observations made of the wear surfaces.

4 RICE PARTICLE MOTION ANALYSIS

4.1 High Speed Photography

High speed photography was used to investigate the motion of rice as it impacted against the rice chute. The counterface was positioned at angles of 0°, 30° and 60° (the latter is the usual design for the rice sorting machine). Individual rice grains were dropped from a height of approximately 30mm, as shown in Figure 14. The rice was dropped in two orientations, end-on and side-on (see Figure 15). Dropping the rice grains onto the horizontal surface allowed the coefficient of restitution to be calculated, which was needed for the analytical calculations of rice motion shown in section 4.2.

It was seen on examination of the video footage that, for both rice orientations, a double impact occurred on first hitting the counterface (for all angles). For end-on drops the friction force at the point of contact caused the grain to rotate. Subsequently it lifted free from the surface and struck again before the grain bounced away (see Figure 15a). For side on impacts, one end impacted first and then the other before the grain left the surface (see Figure 15b).

Rebound angles were determined for the angled counterface tests and rebound heights for the horizontal counterface tests, these are given in Table 2. The coefficient of restitution, e, is also given in Table 2 for the flat tests, which calculated using the following equation:

$$e = \sqrt{\frac{h_2}{h_1}} \tag{1}$$

where h_1 is the drop height and h_2 is the rebound height.

Rebound angle was lower for the 60° angle, as would be expected, and rebound angle was lower for the side on impact. It was clear from the video that the rice grains made little contact with the counterface and that they typically bounced, rather than slid, down the chute. It is possible that with a stream of rice flowing down the chute, these subsequent bounces might have been damped out.

4.2 Analytical Motion Analysis

The equations used for analysing the rice motion during an impact (developed from Newton's work) are usually used for studying the impact of balls. Figure 16 illustrates the situation being examined and some of the key parameters.

It should be noted for the purposes of the calculations outlined below that that the rice grain was assumed to be impacting side on as shown in Figure 16. Coloumb friction is assumed with a constant friction coefficient μ between the rice grain and the counterface surface

The velocity, v_i, at the point of impact can be calculated by using:

$$\tfrac{1}{2}mv_i^2 = mgh_1 \tag{2}$$

Rearranging this gives:

$$v_{\mathrm{i}} = \sqrt{2gh_1} \tag{3}$$

The components of the velocity, v_{xi} and v_{yi} can then be calculated from the impact angle. Initially it has to be determined whether the rice grain is rolling or sliding when it impacts. The grain rolls if [4]:

$$\mu(1+e) \geq \frac{\left(v_{\mathrm{xi_i}} + \omega_{\mathrm{i}} r\right)}{-v_{\mathrm{yi}}} \frac{A}{(1+A)} \tag{4}$$

where ωi is the rotational (spin) velocity of the grain (assumed to be zero is this case), r is the radius of the rice grain (0.95mm), and A is given by:

$$A = \frac{I}{mr^2} \tag{5}$$

where I is the moment if inertia and m is the mass of a rice grain (0.00016g). The value for μ was taken from the friction testing and the value for e from the drop testing. All values calculated are shown in Table 3. There are two separate sets of equations for slipping and rolling. In this case rolling occurred so the following equations were used for calculating the velocity components after the impact:

$$v_{\mathrm{vf}} = \left(\frac{v_{\mathrm{xf}} - A\omega_i r}{1+A}\right) \tag{6}$$

$$v_{\mathrm{yf}} = -ev_{\mathrm{yi}} \tag{7}$$

From these the angle of rebound, $\theta_{\mathrm{f}} = \tan^{-1}\left(v_{\mathrm{yf}} / v_{\mathrm{xf}}\right)$ can be calculated. These angles are shown in Table 3 and compared with the measured values.

The values obtained from the analytical calculations are reasonably close to the measured values, which is encouraging given the broad assumptions made.

5 DISCUSSION

There are two ways in which the wear can be alleviated. The first is through a material change and the second by making design modifications.

The materials tests have shown that the best (and commercially viable) alternative appears to be the hard anodised aluminium or chrome plating which performed better in the wear tests with and without abrasives. There was no real difference between materials in the friction testing, which suggests in terms of rice sliding down the chute none of the materials would present a problem. The function of the chute itself does not directly depend on friction coefficient, provided it remains constant throughout the rice path. If the friction fluctuates during the particle motion it would be difficult to ensure all grains arrived at the detector head in a uniform manner. During these tests no major temporal friction variations were observed.

The main problem is the aluminium substrate; clearly when the hard protective surface layer is worn through the wear to the substrate occurs rapidly. This causes the grains to bounce irregularly down the chute. Aluminium is the base material of choice for reasons of corrosion resistance and cost. A good solution would be to improve the thickness of the outer coating. Thicknesses of hard anodising can be over 0.2mm, depending on the processing method used. This is higher than most chromic processes such as that used and is therefore an advantage.

The major cause of the accelerated wear of the chute is clearly contamination (abrasive husk etc.) present in dirty rice. If operators are to continue using dirty rice then perhaps a mechanism to remove husk could be incorporated before the rice reaches the chute, or perhaps the new wear data could be used to change the recommendations made to operators and/or the defined wear life.

In terms of design, the angle of impact at the top of the chute is important. Work investigating the relationship between erosive wear rates and impact angle [5] (see Figure 17) has shown that a maxima exists for brittle materials at 90° and at about 17° for ductile materials. The anodised layer will be comparatively brittle, so the design angle of 30° is a good choice. However, once this has been worn away the wear rate of the underlying aluminium is likely to be relatively high.

Changing the impact angle would involve substantial design modification. The chute length, rice flow rate, and positioning of detection and sorting heads are configured for a particular travel time down the chute. Any changes to the impact angle will change the path of the rice grains. More subtle changes such as reducing the drop height on to the chute or improving the surface quality to prevent the rice lifting and re-impacting the surface may be more easily undertaken.

The video footage and analytical modelling has shown that a steeper chute angle gives a lower rebound angle, which would be preferable in order to keep the rice sliding down the chute rather than bouncing down it. This kind of analysis could be used to optimise the angle if a design change was carried out.

CONCLUSIONS

Failure analysis has been carried out on a chute from a rice sorting machine. Wear mechanisms have been identified as being a combination of erosion and abrasion. Wear scars at the top of the chute, where rice initially impacts, are uniform in nature. They show small erosion pits ahead of abrasive scratches. The location of wear regions further down the chute are random in nature and may occur due to rice grains bouncing off the chute and re-impacting.

Friction testing using some candidate replacement materials has shown that little difference could be found between the materials. With a clean surface, however, higher friction was seen. The natural contamination caused by rust dust is beneficial in reducing friction forces.

Reciprocating wear testing showed that hard anodised and chrome plated aluminium offered the best resistance to wear both with and without abrasive present. Wear rates of all materials increased by an order of magnitude with abrasive in the rice contact.

High speed video footage of rice impacts at a variety of angles and impact positions has shown that rebound angle decreases with increasing chute angle. Analytical modelling carried out to calculate rebound angles (using inputs from the friction testing) compared well with the actual values. This technique could be used to optimise the design of the chute.

A thicker anodised or plated layer would be beneficial as after the protective surface coating has been removed the wear of the base aluminium will occur relatively quickly. Hard anodising can offer a thicker coating than the chrome plating process and offers a good solution.

REFERENCES

1. J.S. Rivas, J.J. Coronado, A.L. Gomez, Tribological aspects for the shafts and bearings of sugar cane mills, in press, Wear (2006).
2. L.C. Seabra, A.M. Baptista, Tribological behaviour of food grade polymers against stainless steel in dry sliding and with sugar wear, Wear 253 2002, 394-402.
3. F.P. Bowden, L. Leben, The nature of sliding and the analysis of friction, Proceedings of the Royal Society A169 1939, 371-91.
4. C.B. Daish, The Physics of Ball Games, Hodder and Stoughton, 1981.
5. I.M. Hutchings, Friction and Wear of Engineering Materials, CRC Press, 1992.

Figure Captions

Figure 1. Schematic of the Rice Feeding and Sorting Machine

Figure 2. Rice Chute and Position of Wear Scars: (A) Unworn Material; (B) Ridge Wear Scar; (C) Top Wear Scar; (D) Channel Wear Scar and (E) Bottom Wear Scar

Figure 3. (a) Top of the Rice Chute and (b) Bottom of the Rice Chute

Figure 4. Micrograph of Unworn Chute Surface (point A).

Figure 5. Micrographs of (a) Top and (b) Bottom of Wear Scar at the Top of the Chute (point C).

Figure 6. Surface of Wear Track seen in Chute Channel (point D)

Figure 7. Micrographs of (a) Top and (b) Bottom of Wear Scar at the End of the Chute (point E)

Figure 8. Friction Measuring Rig

Figure 9. Friction Results for Loads of (a) 40N and (b) 60N

Figure 10. High Frequency Reciprocating Rig (a) Schematic Diagram of the Test Head and (b) Photograph of the Apparatus.

Figure 11. Wear Surfaces before and after Testing

Figure 12. Wear Surfaces with SiC Particles

Figure 13. Wear Volumes

Figure 14. Rice Drop Test Set-up and stills from a Drop Test

Figure 15. Schematic Diagram of Rice Motion for (a) an End on Impact and (b) a Side on Impact

Figure 16. A Rice Grain Impacts a Rigid Surface with Velocity, and (possibly) Positive Spin (anticlockwise) such that the Grain Experiences Forces *R* and *F* from the Surface

Figure 17. Erosive Wear Rates for Brittle and Ductile Materials versus Impact Angle [4]

Table Captions

Table 1. Details of Materials Tested

Table 2. Drop and Rebound Heights and Angles

Table 3. Results of Analytical Rice Motion Calculations

Figure 1

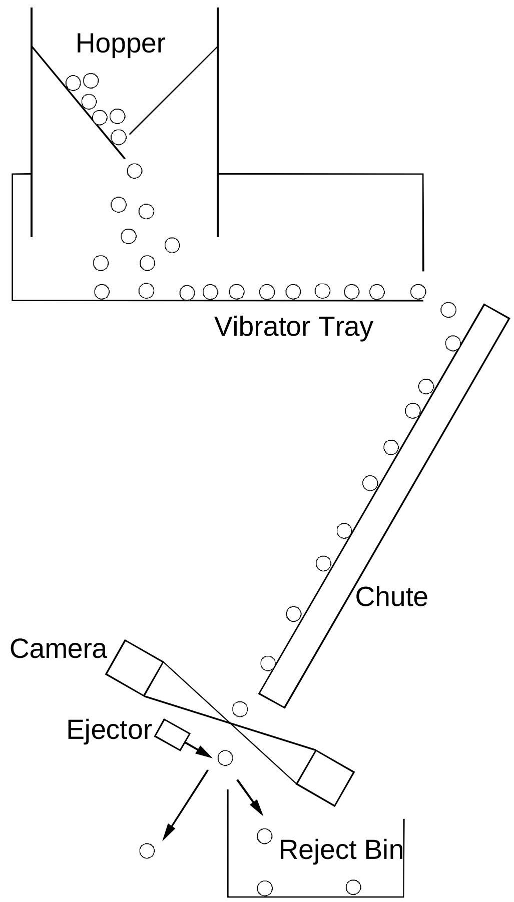


Figure 2

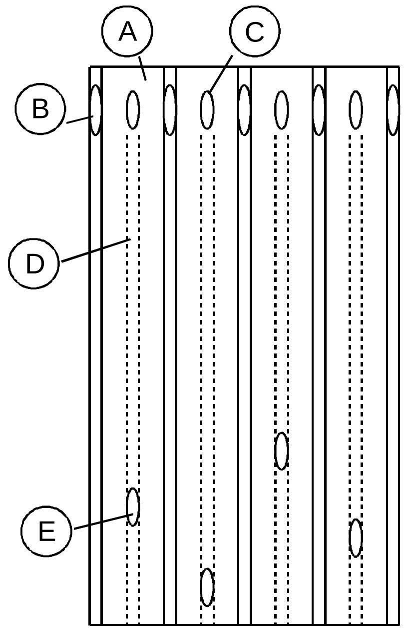


Figure 3

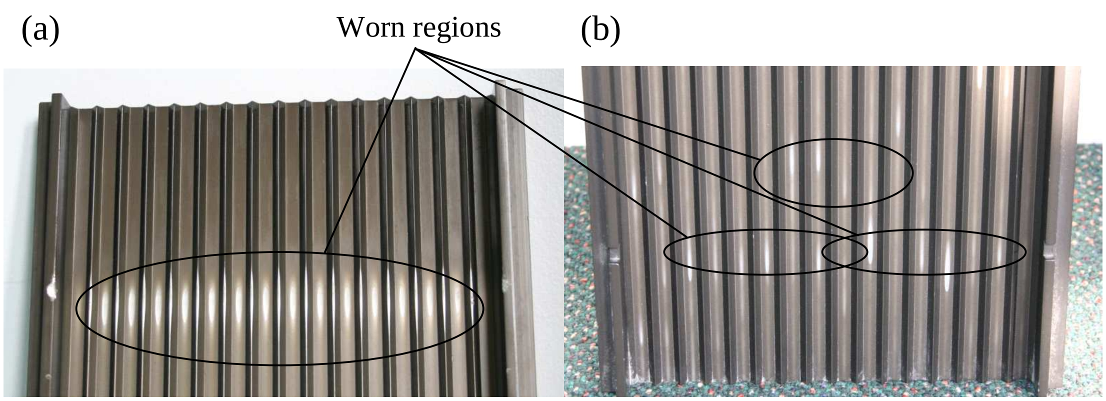


Figure 4

Figure 5

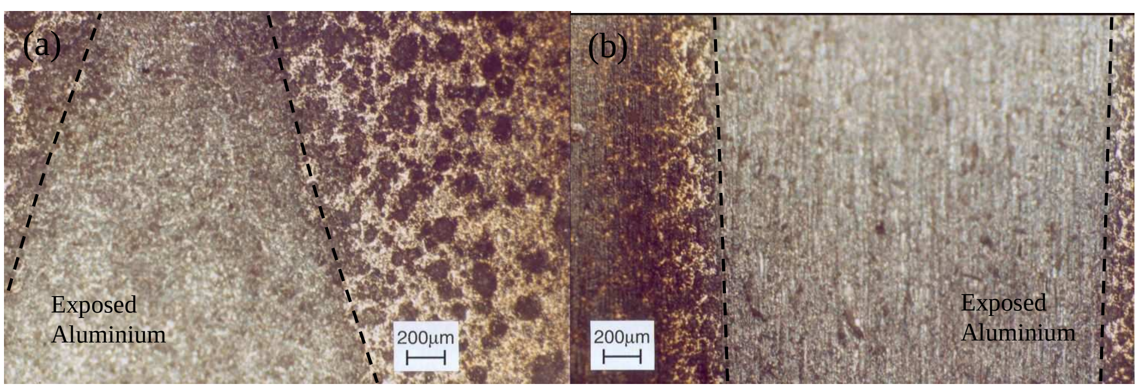


Figure 6

Figure 7

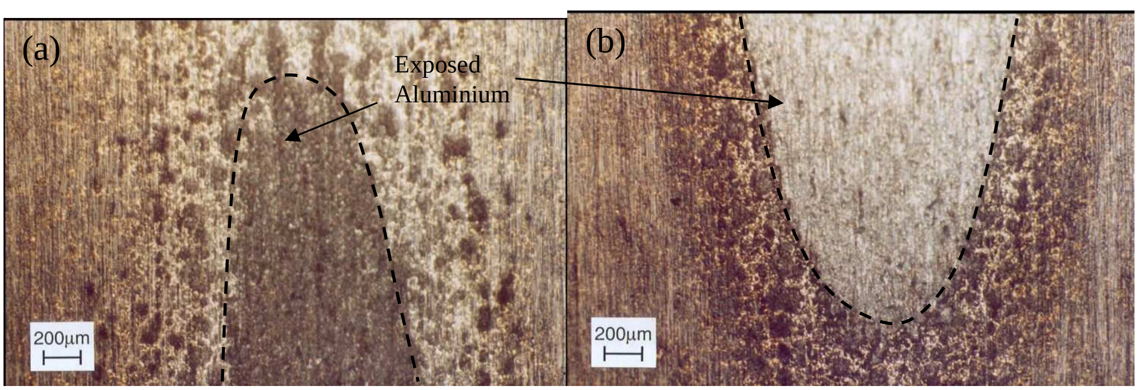


Figure 8

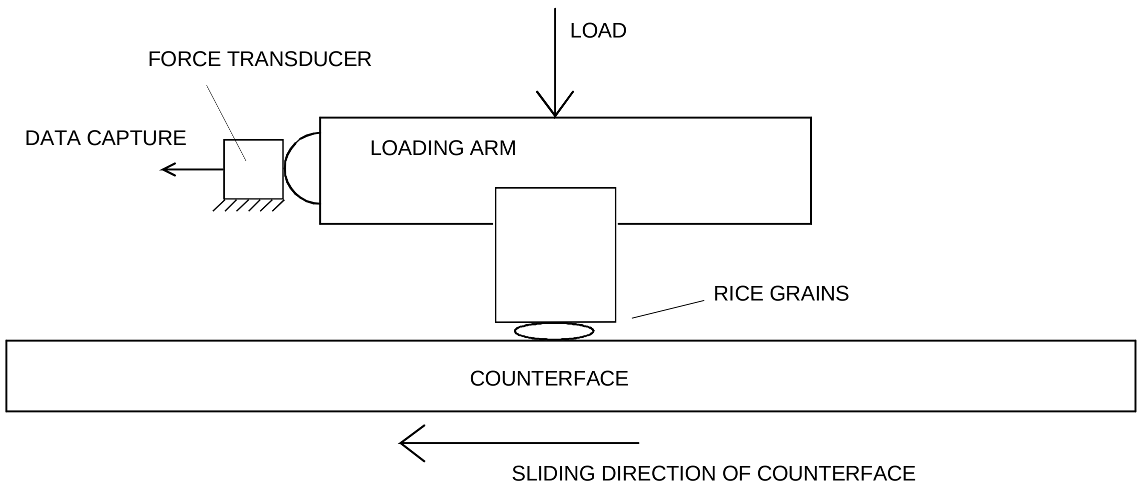


Figure 9

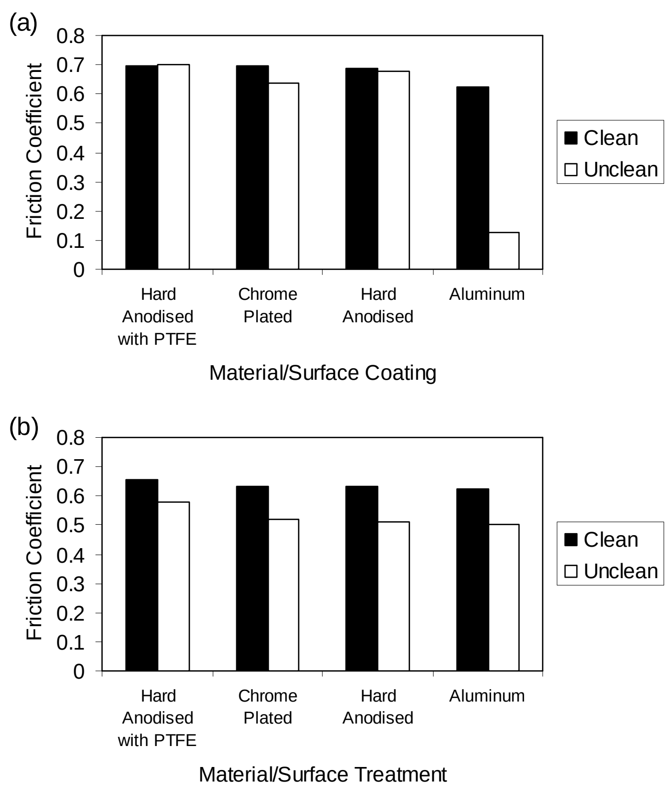
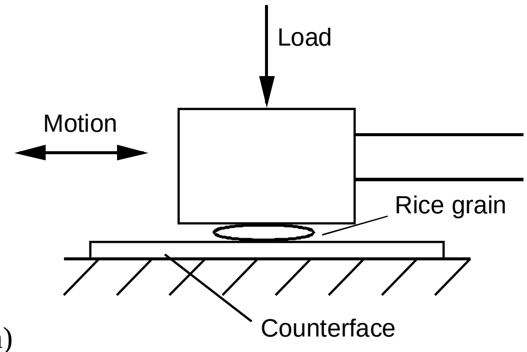
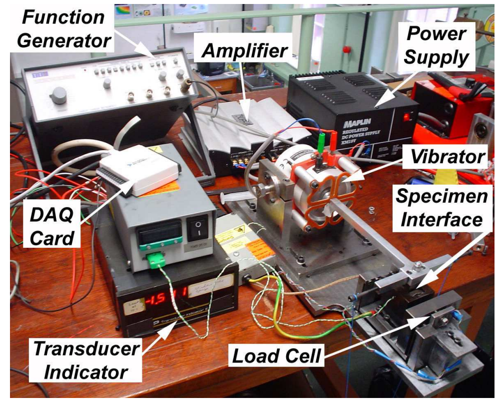


Figure 10



Load
Motion
Rice grain
Counterface

(a)



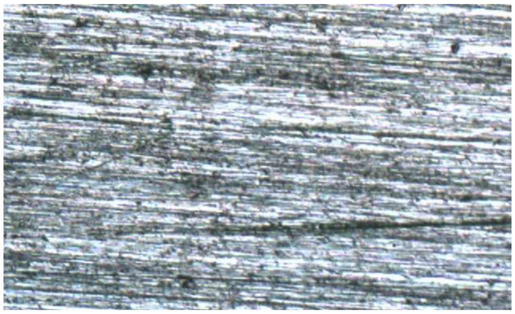
Function Generator
Amplifier
Power Supply
Vibrator
Specimen Interface
DAQ Card
Transducer Indicator
Load Cell

(b)

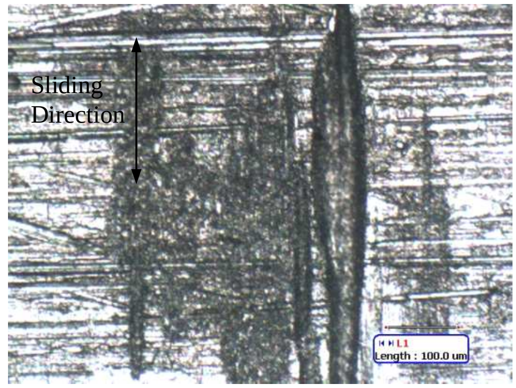
Figure 11

(a) Aluminium

Unworn

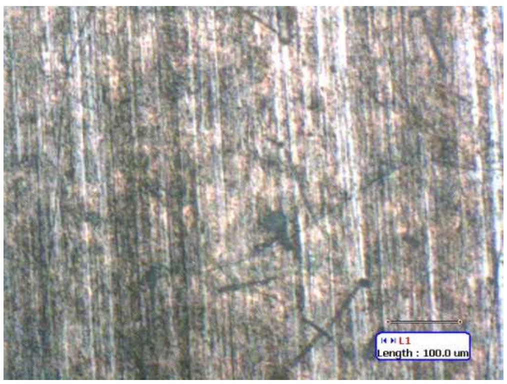


Surface after 30minutes

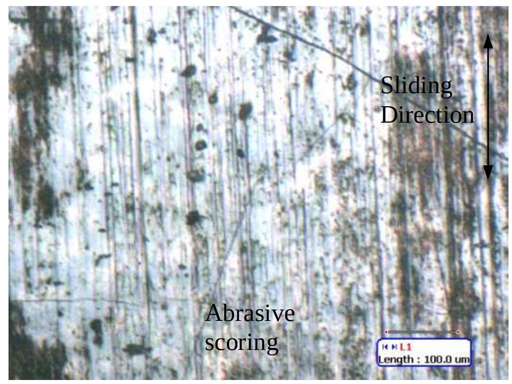


(b) Hard Anodising with PTFE

Unworn



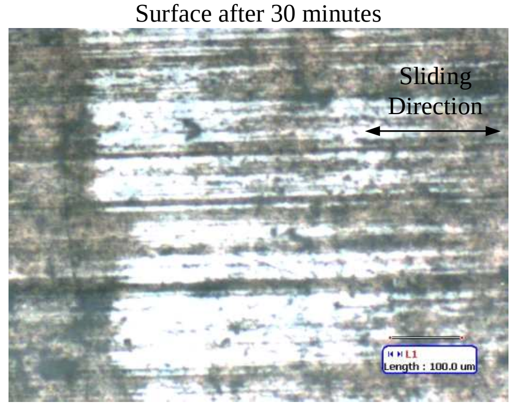
Surface after 30 minutes



(c) Chrome Plating

Unworn

Surface after 30 minutes



(d) Hard Anodised

Unworn

Surface after 30 minutes

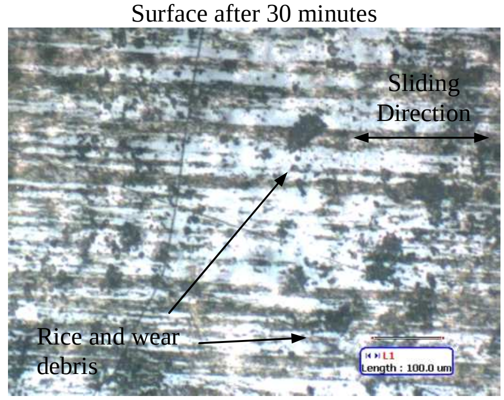


Figure 12

(a) Hard Anodising with PTFE (b) Hard Anodised

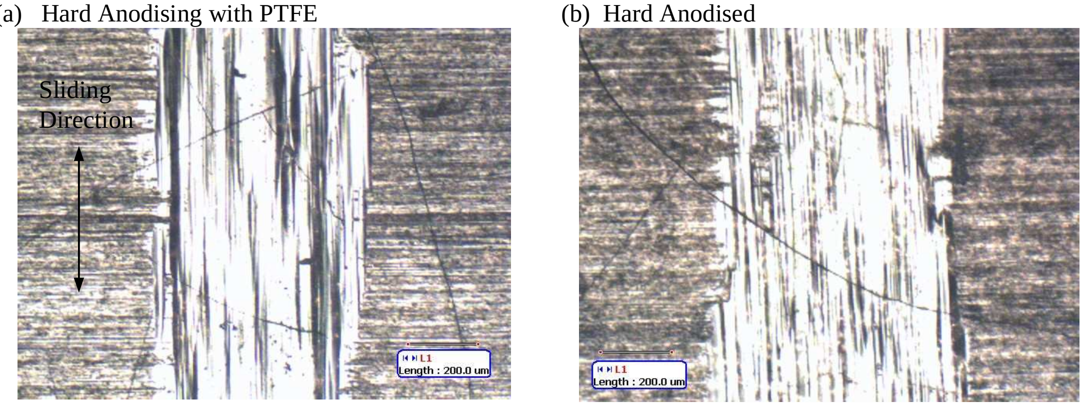


Figure 13

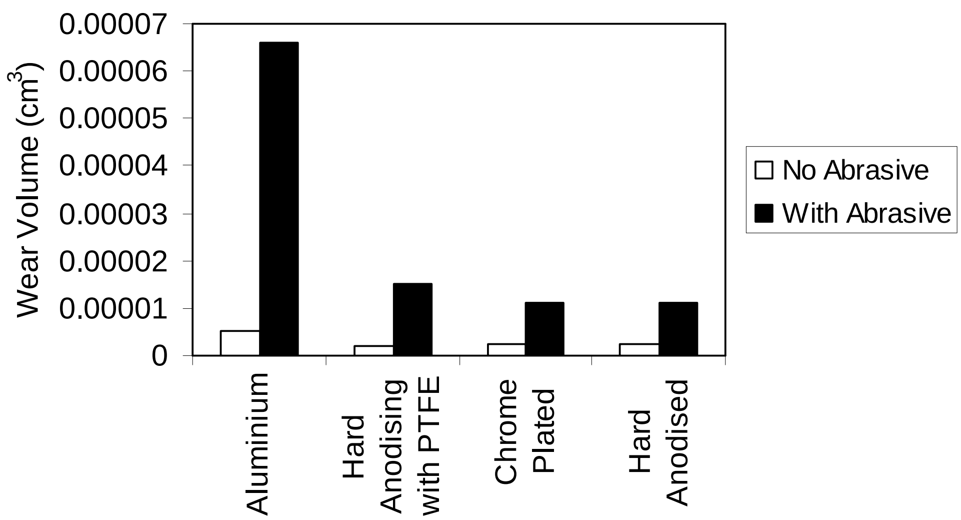


Figure 14

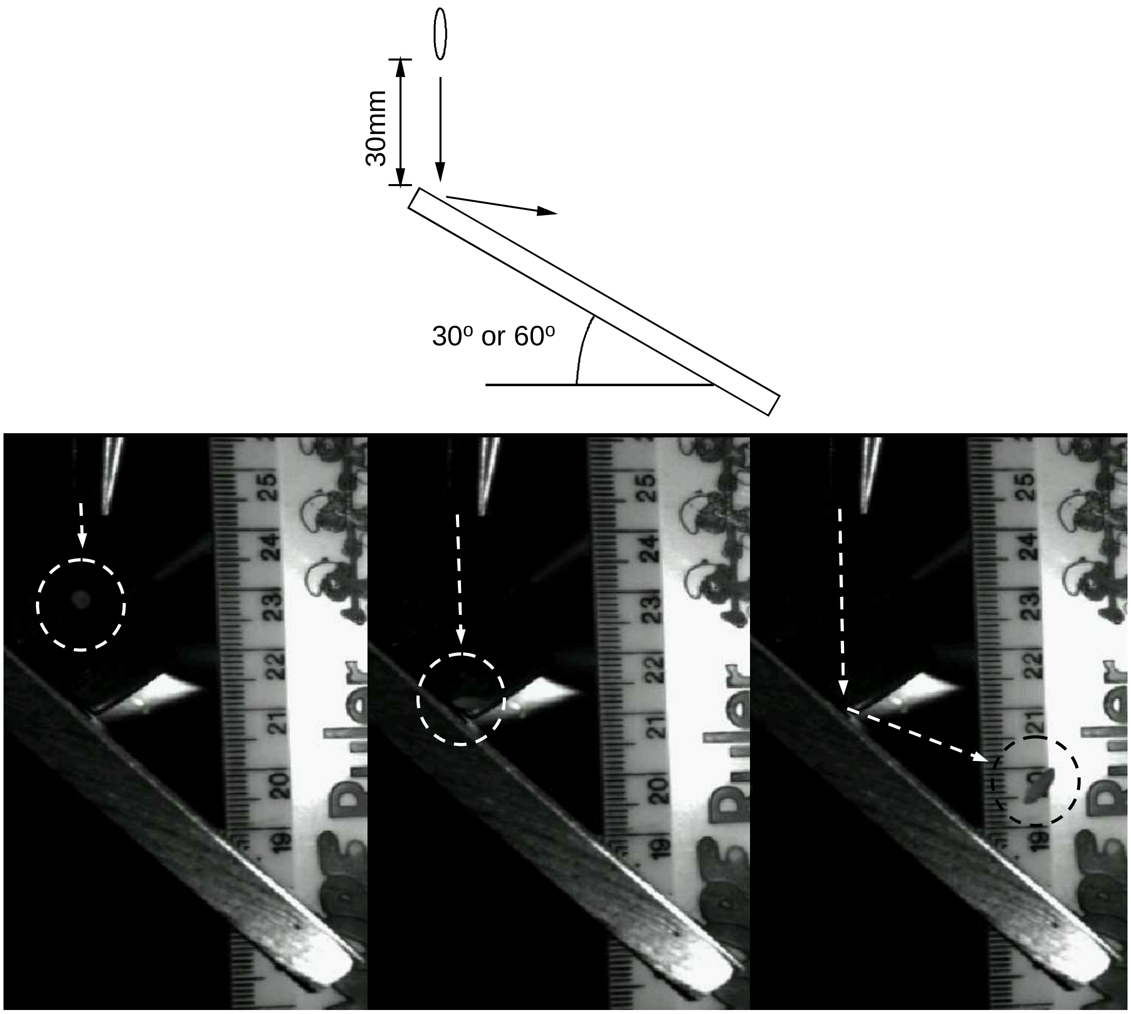


Figure 15

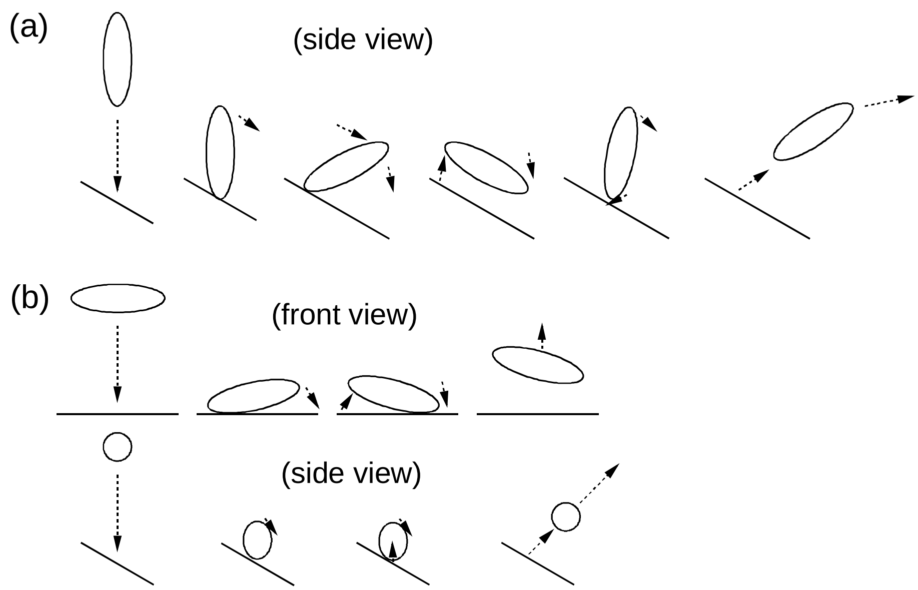


Figure 16

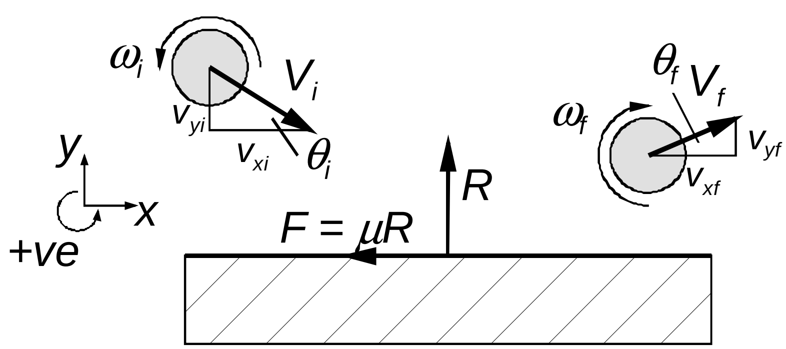


Figure 17

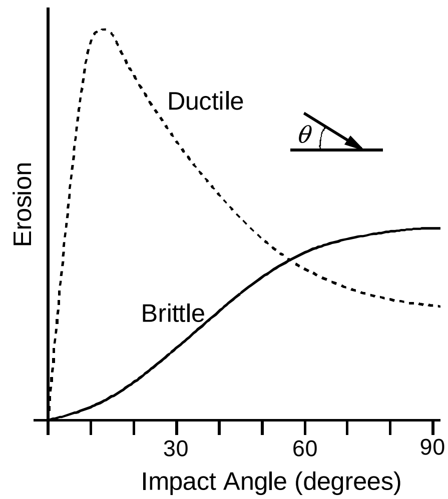


Table 1

Material/Surface Treatment	**Vickers Micro-Hardness (100g)**	**Roughness (Ra, μm)**
Aluminium	124	0.159
Hard Anodising	407	0.429
Hard Anodised with PTFE impregnated	462	0.479
Chrome Plating	346	0.406

Table 2

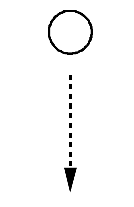
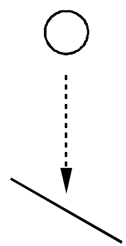
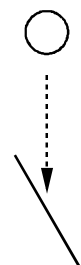
0° 			30° 				60° 			
—					—				—	
h_1 (mm)	h_2 (mm)	e	h_1 (mm)	θ (°)	h_1 (mm)	θ (°)	h_1 (mm)	θ (°)	h_1 (mm)	θ (°)
38	14	0.61	30	34	30	45	30	31	30	27
35	15	0.65								
		Avg: 0.625								

Table 3

h_1 (mm)	Impact angle (°)	v_i (m/s)	v_{xi} (m/s)	v_{yi} (m/s)	μ	e	$\mu(1+e)$
30	30	0.76	0.65	-0.38	0.53	0.625	0.86
30	60	0.76	0.38	-0.65	0.53	0.625	0.86

$\frac{(v_{xi_i}+\omega_i r)}{-v_{yi}} \frac{A}{(1+A)}$	Rolling/Sliding	v_{xf} (m/s)	v_{yf} (m/s)	θ_f (°) (predicted)	θ_f (°) (measured)
0.57	Rolling	0.25	0.41	58	45
0.19	Rolling	0.43	0.24	28	27