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Direct observation of frictional seizure of mild steel sliding on aluminum by X-ray imaging

Part II *Mechanism*

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Observation of frictional contacts has always been a problem for long as the contact is normally hidden. In this work, we have used an X-ray microscope for in-situ observation of frictional seizure, wear and interfacial features during the testing of mild steel specimens sliding against Al 6061 disk. This technique enables the observation of interfacial features of the hidden contact. Seizure tests were conducted at different sliding speeds of 2, 4 and 5 m/s. The images obtained during the tests indicated that the wear process was a combination of random transfer events and cyclic process of a close contact followed by a partial separation of the sliding surfaces. Wear was concentrated over a certain specific area during the initial part of the test but later the contact developed into a conformal contact following a lumpy transfer of material. The mechanisms of seizure and wear were affected by the sliding speed. At a sliding speed of 4 and 5 m/s, the transfer and bonding of material was not directly caused by nascent surface contact but due to contact of rolled and compacted wear debris with the nascent surfaces. Whereas at lower sliding speed (2 m/s) the transfer and bonding of deposits occurred due to direct contact of nascent sliding surfaces. © *2000 Kluwer Academic Publishers*

1. Introduction

Various researchers, have studied friction and wear behaviour and seizure of frictional contacts owing to their increased importance over the last few decades. However, most of the mechanisms proposed were based on post test observations leading to debate over the mechanisms so proposed. To overcome this lacuna direct observation of friction and wear phenomena were done using conventional analytical tools such as scanning electron microscope (SEM), Optical tools and video camera [1–4]. Though these tools helped in understanding the process in a greater detail were limited to the observation of leading and trailing edges of the contact. In this work an X-ray microscope has been used for in-situ observation of frictional seizure with parallel measurement of the experimental parameters. The present work is also aimed at gaining a better understanding of the interfacial process during sliding.

2. Experimental procedure

Experiments were performed using a custom built pin on disk apparatus. The pins were supported using a tool steel holder fitted on to an aluminium beam to facilitate application of normal load and observation of subsurface features of the specimen. Aluminum was selected as the disk material for two reasons 1) Increased application in weight saving applications and 2) to have minimal attenuation after passing through the contact to get a sharper image revealing the interfacial features. Fig. 1 shows a schematic representation of the experimental setup showing the details of image acquisition and processing stages. A FeinFocus X-ray microscope with a beam spot size of 4–20 μm diameter was used in all experiments. Mild steel pins of dimension ϕ 5 mm $\times$ 3 mm thick specimens were polished using a 1000 grit SiC abrasive paper to provide a surface roughness value of Ra 0.03–0.05 μm and was fixed to specimen holder designed to facilitate X-ray observation. The counterface disks were made of Al 6061 machined and fine turned to the roughness value of 0.04–0.06 μm Ra value with a skewness and kurtosis of 1.7 and 3.4 respectively. The experiments were carried out at sliding speeds of 2, 4 and 5 m/s. The normal load was increased until seizure during the tests in steps spaced at 15 minutes interval for tests conducted at a sliding speed of 4 and 5 m/s. The load in case of 2 m/s sliding was however constant at 0.9 MPa as an early indication of scuffing was observed by the way of stick slip phenomenon. Since X-rays get differentially absorbed in the specimen due to the changes in the specimen during the test, the transmitted X-ray intensity suffers similar variational effects, which is reflected back on the visible light image developed on the screen. The images developed on the fluorescent screen was captured using a high speed digital camera with a shutter speed of 500 frames/seconds attached to the microscope and the

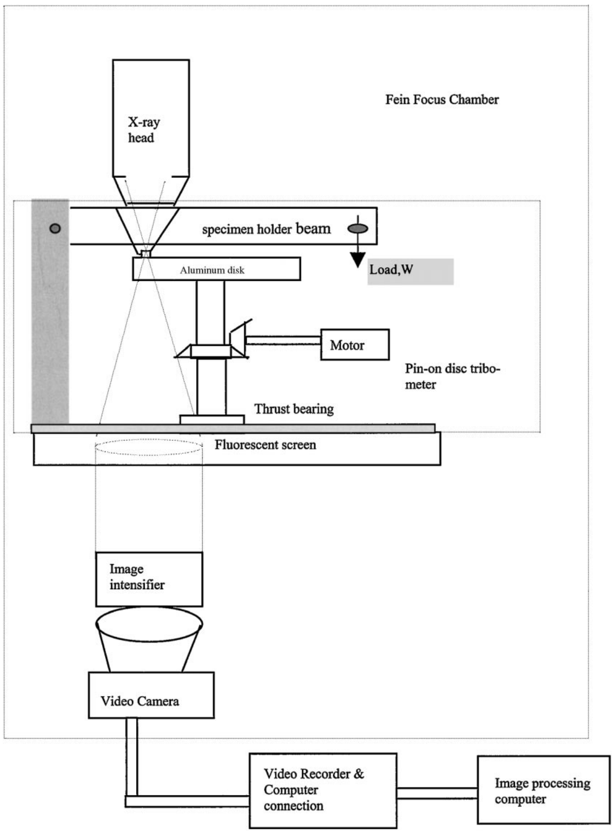


Figure 1 Schematic representation of the test apparatus and the image processing system.

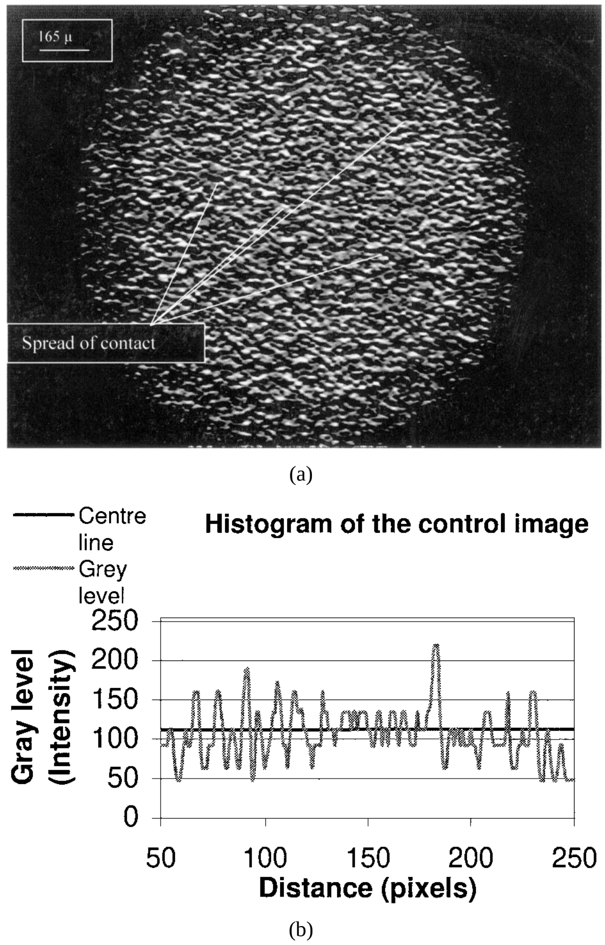


Figure 2 (a) Control X-ray fluoroscopic image of the MS pin/disk interface tested at 5 m/s; (b) histogram of control X-ray fluoroscopic image of MS pin/disk tested at 5 m/s along the centre line.

associated noise in the image was filtered using a synoptic recursive filter to get a noise filtered image on the screen. This was further processed to highlight certain important changes during sliding governing the mechanism of the wear process. The X-ray intensity was fixed at 76 kV and the current density was 53 μA for focusing the X-ray beam approximately at the interfacial layer. The images were collected at specified intervals of time and 1 minute was the typical period between observations to monitor the changes in real-time. The main purpose being observing the images with the progress of wear and also to identify the driving mechanism of seizure at a particular position.

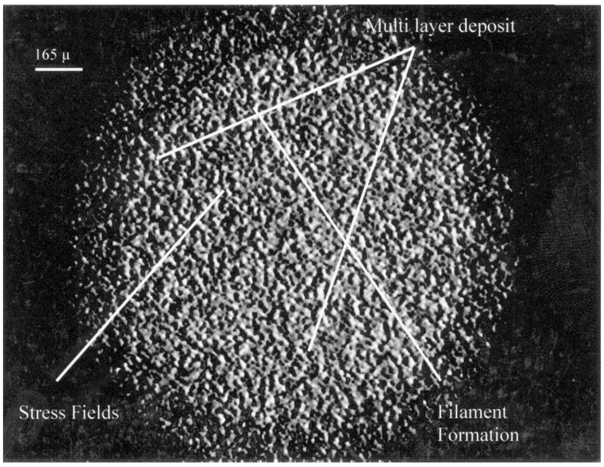
3. Results

Figs 2–7 show the X-ray fluoroscopic images of mild steel sliding on Al 6061 disk at a speed of 5 m/s. The sliding behavior at 2 m/s and 5 m/s sliding speeds were observed to be quite different.

Fig. 2a and b show the control image and the representative histogram profile along the horizontal centre line of the image, which represents the initial contact in the form of gray level difference. This shows fairly a uniform contact and a surface free from defects. The white spots in the images tentatively indicate areas where the contact is not established. This is due to the fact that the attenuation of X-rays are lower when it passes through a air gap rather than through the material contact and flattening of lines indicate plastic flow and spreading of contact.

Fig. 3a and b, the fluoroscopic image of the interface after 30 seconds of sliding and the representative histogram profile along the horizontal centre line of the image, indicated fracture and rolling of asperities. It is also seen that the contact was not restricted to a single area and greater number of white spots was observed which tentatively indicates area of non-contact zones. The patches having similar gray levels separated by boundary lines identify formation of wear debris pressed to form sheets. Spots where peaks were observed before the start of the test have developed into valleys due to asperity fracture and those areas which were valley at the start have become a peak/asperity to establish new contact points. The image also shows roughening of the surface due to sliding and multiple layer formation on the pin surface which results in build-up of layers of wear sheets after 1 minute of sliding. There is evidence of deformation network bands due to the strain fields generated during sliding. This is inferred from the peak broadening in the histogram profile. A few of the wear sheets generated during sliding were rolled into a filament on the surface of the pin and this was observed on the surface as protrusions, which had a histogram profile resembling a curvature. Plateau formation was also evident amidst of the adhered layers of Al and the friction coefficient was at 0.77.

Fig. 4a and b shows the X-ray fluoroscopic image of the interface after 1 minute of sliding at 5 m/s and the representative histogram profile along the horizontal centre line of the image. This image shows multi-layer deposit of aluminium on to the mild steel specimens



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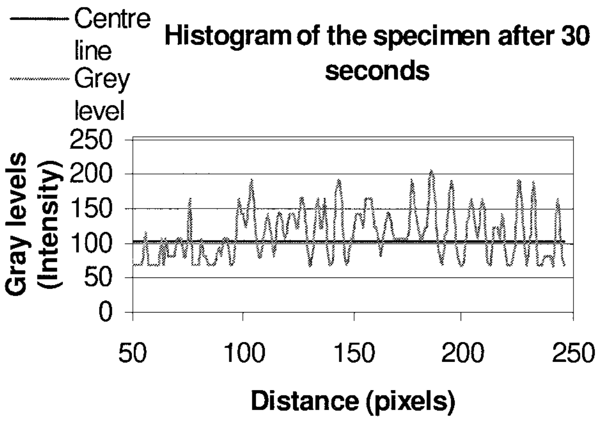
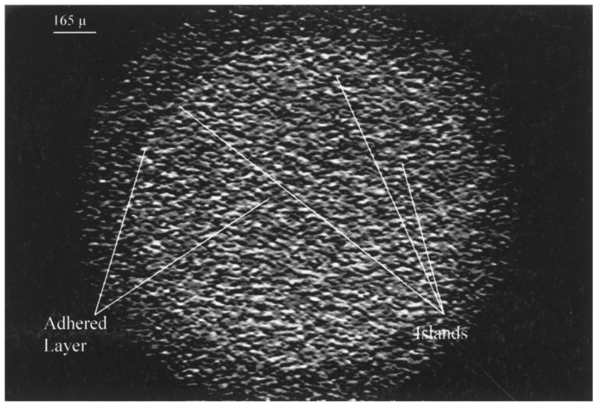


(b)

Figure 3 (a) X-ray fluoroscopic image of the MS pin/disk interface after 30 seconds of sliding at 5 m/s; (b) histogram of image along the centre line, after 30 seconds of sliding at 5 m/s.



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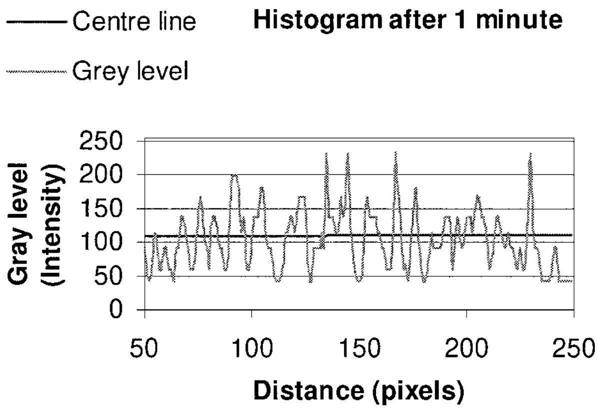


(b)

Figure 4 (a) X-ray fluoroscopic image of the MS pin/disk interface after 1 minute of sliding at 5 m/s; (b) histogram of image along the centre line, after 1 minute of sliding at 5 m/s.

evident from the stepped variation in gray levels of the histogram and plateau formation on the surface as is evident from the difference in gray levels of the image around the centre. The lines at the edges of the image are representative of multiple layers of material since a difference in gray level is due to the difference in absorption of X-rays by the material through which it passes through. The difference in absorption arises due to any changes in material such as a deposit/deposition of layers.

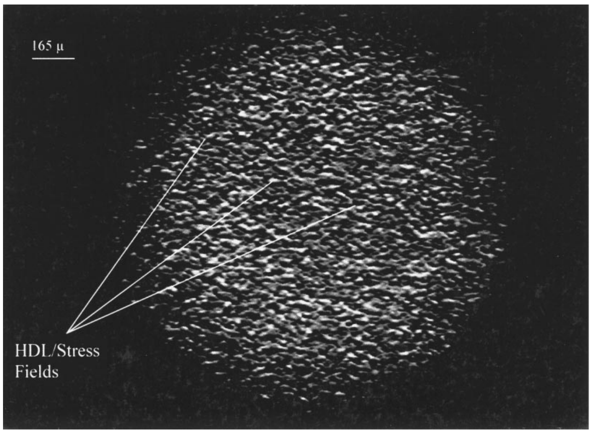
Fig. 5a and b show the X-ray fluoroscopic image of the MS pin/ Al disk interface 1 minute before the actual seizure and the representative histogram profile along the horizontal centre line of the image. The image again is of a lower intensity i.e., the gray levels are essentially on the lower side. The central region of the pin interface appears to have a jagged appearance, which is due possibly to the accumulation of stress fields and formation of a highly deformed layer. The image also indicated some small pit like depressions, which are due possibly to the micro plowing.

Fig. 6a and b shows the X-ray fluoroscopic image of the MS pin/ Al disk interface 30 seconds before the actual seizure and the representative histogram profile along the horizontal centre line of the image. This shows considerable rough surface generation leading to a severe stick slip condition in the sliding confirmed by the fluctuations in the gray levels and the coefficient of friction traces. There was some isolated point welding between the pin and the disk surface that were indicated by a small reduction in the intensity/gray level of the image matrix especially in the upper region of the image.

Fig. 7a and b shows the X-ray fluoroscopic image at seizure of aluminium/steel pair and the representative histogram profile along the horizontal centre line of the image. The layered deposit of the Al on the steel pin is evident from the profile of gray level differences observed in those regions. This image had more or less uniform gray level throughout the matrix indicating that the Al had deformed and had flown into the plateau generated on the pin surface to establish conformal contact. This result in a strong mechanical joint combined with isolated metallurgical bond to restrict further sliding. The darker regions in the image near the centre represent the metallurgical bond.

Fig. 8 shows the SEM picture of the MS pin surface tested at 5 m/s under dry sliding conditions. The transferred aluminium appeared to have flown plastically and generated a smooth soft surface on the mild steel. The transferred aluminium also appears to have extruded to accommodate the normal load on the specimen. EDX analysis of the surface indicates the presence of a high intensity Al peak and a Fe peak meaning that the pin surface was covered with transferred aluminium from the disk.

Fig. 9 shows the SEM image of the wear track on the disk surface tested at 5 m/s under dry conditions where



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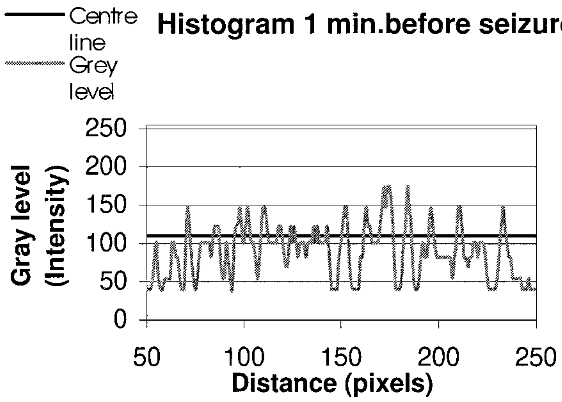
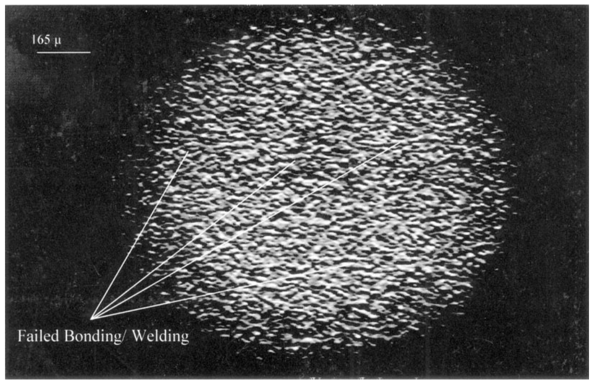


(b)

Figure 5 (a) X-ray fluoroscopic image of the MS pin/disk interface 1 minute before seizure tested at 5 m/s; (b) histogram along the centre line of the X-ray fluoroscopic image of MS pin/disk tested at 5 m/s, 1 minute before seizure.



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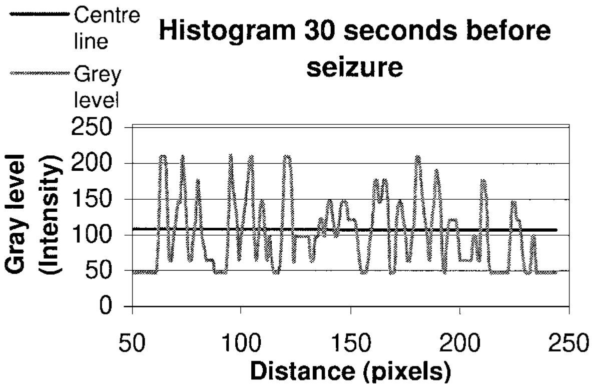
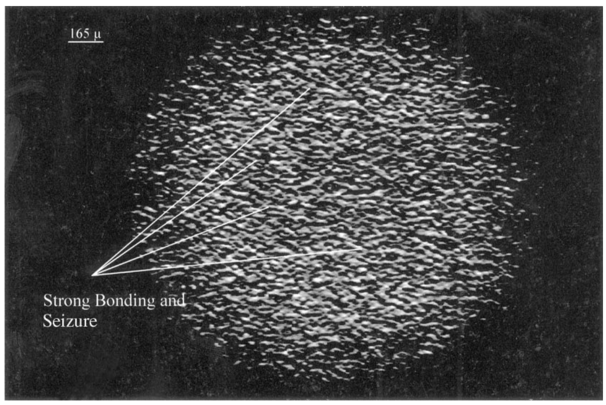


(b)

Figure 6 (a) X-ray fluoroscopic image of the MS pin/disk interface 30 seconds before seizing tested at 5 m/s; histogram of image along the centre line, 30 seconds before seizure tested at 5 m/s.



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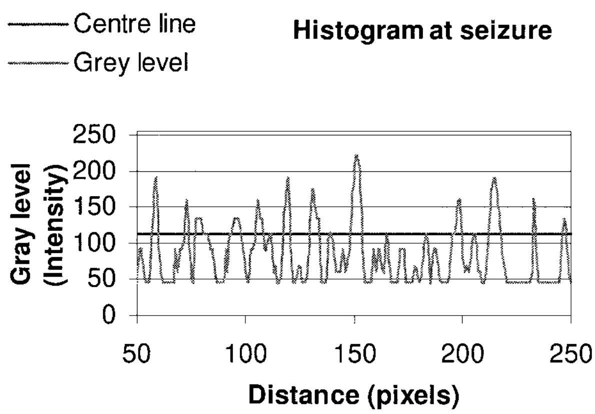

(b)

Figure 7 (a) X-ray fluoroscopic image of the MS pin/disk interface at seizure tested at 5 m/s; (b) histogram of image along the centre line, at seizure tested at 5 m/s.

back transfer and extrusion of the transferred layers to accommodate sliding can be seen. Possible indications of fatigue failure were also present on the wear track. EDX analysis of the disk surface on the wear track revealed the presence of Al, Si, Cu, O and Fe on the track. The presence of oxygen may signify oxidation of transferred/back transferred Aluminium.

Figs 10 and 11 presents the graphical representation of the variation of experimental parameters with the test. The observations such as roughening and incipient bonding from the fluoroscopic images were made using the basic principles of image processing and fluoroscopy discussed before in this thesis and correlating the same with the stick slip and rise in friction coefficients and the rise in temperature. The coefficient of friction was found to vary from 0.4–0.8 during the test. Stick-slip was not as severe as in the case of 2 m/s-sliding test. However, the wear traces showed negative wear indicative of adhesive transfer. There was a large drop in the wear depth after 10 minutes of sliding, which is due possibly to the lumpy transfer.

4. Discussion

The seizure of mild steel pin tested against aluminum discs at a sliding speed occurs predominantly by adhesive transfer and formation of mechanical locking of the plateau's formed during sliding. The adhesive transfer is possibly enhanced by the higher solubility of Al in Fe

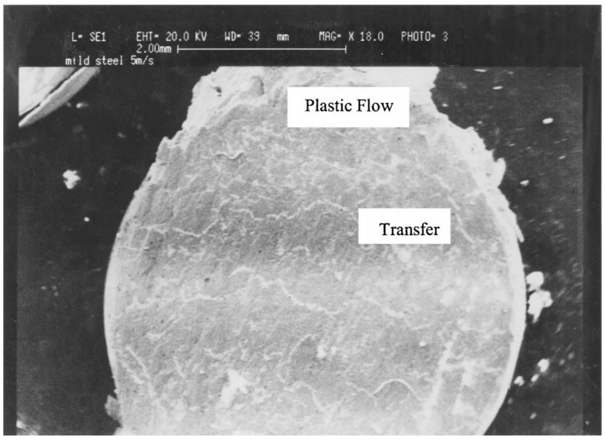

Figure 8 Scanning electron micrograph of the MS pin surface tested at a sliding speed of 5 m/s.

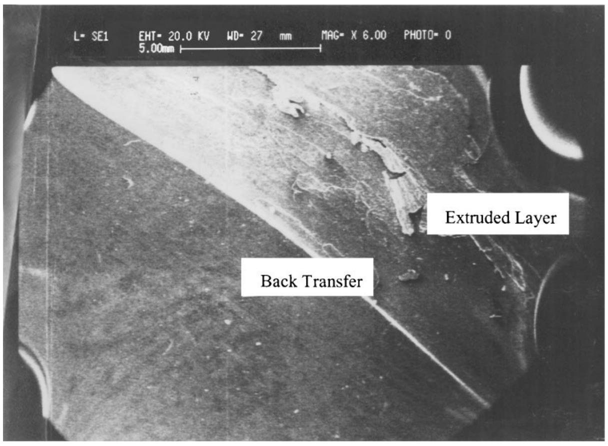

Figure 9 Scanning electron micrograph of the wear tracj on the disk tested at a sliding speed of 5 m/s.

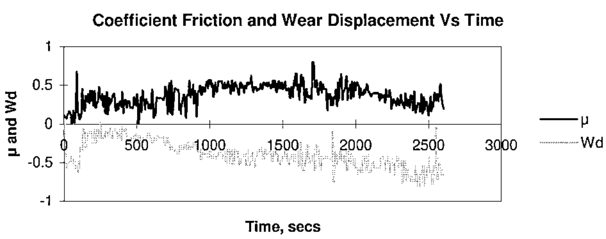

Figure 10 Coefficient of friction and Wear displacement vs. time for MS specimens tested at 5 m/s.

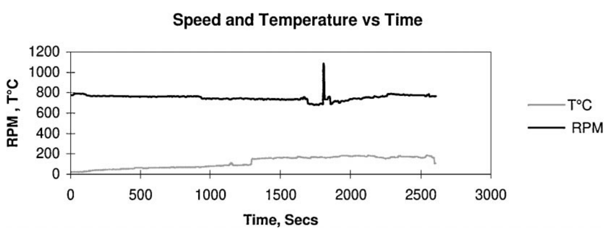

Figure 11 RPM and Temperature (bulk) versus time for MS specimens tested at 5 m/s.

(∼22%) [5–8]. The wear particles generated in the tests at a sliding speed of 4 & 5 m/s due to asperity contact and fracture of these asperities due to shearing action. Wear particles thus generated are entrapped within the sliding contact on the contrary to the behavior observed at 2 m/s. The generated wear particles are pressed to form wear sheets under the action of normal load. These are simultaneously rolled into filaments due to the relative sliding of the surfaces. The rolled filaments are slightly thicker than the original thickness of the parent wear sheets from which it is rolled. The rolled filaments then tries to lift the specimen surface thereby giving a pseudo negative wear depth on the displacement sensor. These filaments are subsequently pressed together to form a layer of worn aluminum which then adheres to the steel surface by forming a bond under the action of normal force. The worn aluminum layer adheres more strongly to the steel surface due to enhanced diffusion at the frictionally elevated temperatures. This results in formation of a relatively weak interface with Al 6061 disk surface due to the contamination of the worn material by the surrounding atmosphere. This wear sheet formation also contributes to the severe surface roughening of Al 6061 disk surface. This cycle repeats in until a steady state condition is reached and sliding condition changes to worn aluminum layer sliding on Al 6061 disk and the surface experiences lower wear rates as compared to initial stages of sliding. Once the above said condition was reached the load was deliberately increased so as to induce seizure. The increase in load further contributed for peeling of adhered worn aluminum layers which then acted as a third body abrasive to contribute to plowing in and generation of wear particles which then rolled into filaments. This was pressed together to form similar worn layer of aluminum but with lesser contamination as the generated particles are masked from the atmosphere partially by the peeled layers of worn aluminum from steel surface. The new layers possibly adhered onto the Al surface due to lesser

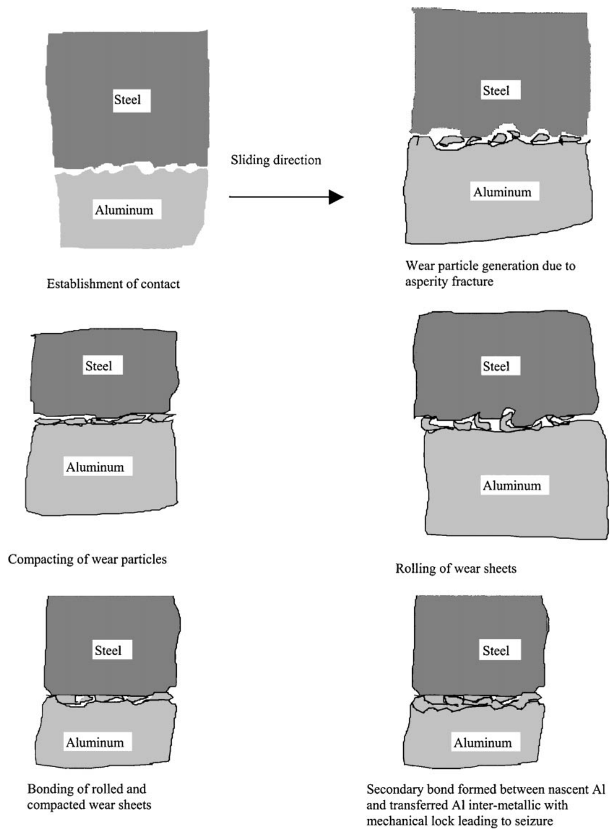

Figure 12 Model showing the onset of seizure.

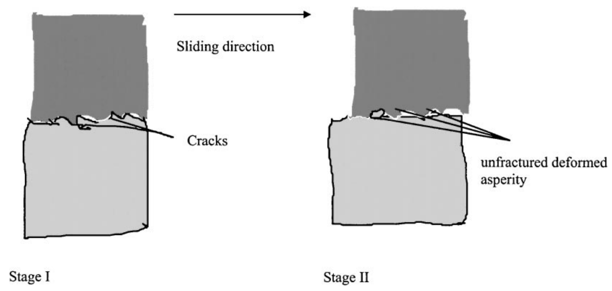

Figure 13 Model showing the wear debris generation at a sliding speed of 5 m/s.

contamination and better affinity towards the parent surface from which it was generated. Seizure may have occurred because of welding of layers of worn aluminum on both the contacting surfaces and mechanical locking of asperities. Evidence for this is presented in Fig. 13 which shows isolated patches of adhered layers with some depressions indicative of mechanical lock. The model of layer formation and mechanical locking is illustrated in Fig. 12, which shows a schematic outline of the processes governing seizure.

At 5 m/s sliding speed, the rate of sliding was faster compared with the crack growth rate and fracture of asperities which possibly resulted in entrapment of the generated wear particles in the contact and deformation of the entrapped wear particles. The entrapped particles rolled as sliding-proceeds to form thin filaments form wear sheets. These wear sheets adhere onto the pins giving rise to a lift off and thereby sensed as negative wear by the laser displacement sensor. Fig. 13 shows the mechanism of entrapment of wear particles during siding at 5 m/s .

5. Conclusion

A pilot study of dry sliding contact between aluminum and steel where an X-ray microscope enabled *in-situ* observations of the sliding contact provided evidence for the following conclusions.

1. By applying the principle of radiography and image processing various subsurface phenomena can be identified during sliding.
2. Wear was chaotic and yet had cyclic behaviour as identified from the profile of the histograms at different stages of sliding
3. Sliding speed was found to have considerable effect on the mechanism of seizure of mild steel in dry contact.
4. The reduction in gray levels of the image to zero and rapid fluctuations in gray level over isolated areas indicate the imminence of seizure in dry contacts.
5. Temperature has little or no effect on the seizure behaviour of steel at lower sliding speeds. Normal load and mutual solubility control the seizure behaviour at lower sliding speeds.
6. At higher sliding speeds the seizure occurs predominantly due to diffusion across the boundary of the surfaces aided by a large frictional temperature rise during sliding.
7. Contaminants and formation of oxide formation delays the onset of seizure of sliding surfaces by providing a protective barrier against surface interactions.
8. The mutual solubility of sliding surfaces plays a vital role in seizure of sliding contacts.

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