Surface folding in metals: a mechanism for delamination wear in sliding

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Using high-resolution, in situ imaging of a hard, wedge-shaped model asperity sliding against a metal surface, we demonstrate a new mechanism for particle formation and delamination wear. Damage to the residual surface is caused by the occurrence of folds on the free surface of the prow-shaped region ahead of the wedge. This damage manifests itself as shallow crack-like features and surface tears, which are inclined at very acute angles to the surface. The transformation of folds into cracks, tears and particles is directly captured. Notably, a single sliding pass is sufficient to damage the surface, and subsequent passes result in the generation of platelet-like wear particles. Tracking the folding process at every stage from surface bumps to folds to cracks/tears/particles ensures that there is no ambiguity in capturing the mechanism of wear. Because fold formation and consequent delamination are quite general, our findings have broad applicability beyond wear itself, including implications for design of surface generation and conditioning processes.

1. Introduction

A central development in modern tribology, beginning with the pioneering work of Bowden & Tabor [1], Holm [2] and Ernst & Merchant [3] is the recognition of the role of plastic deformation of asperities in understanding sliding friction and wear in metal–metal contacts. This has enabled a micromechanical characterization of friction in the adhesive and abrasive
Figure 1. (a) Schematic of the experimental set-up and (b) parameters. The convention used to define the sign of the rake angle is also shown. (Online version in colour.)

wear regimes, and of the formation of surface defects and wear particles in sliding [4–7]. Sliding is also used as a means for imposing large plastic strains on surfaces as with surface conditioning (forming) processes in metals; examples include friction stir processing, burnishing, shear spinning, surface mechanical grinding and even machining [8–11]. Intrinsic to these sliding contacts is unconstrained plastic flow, which differs from the constrained flow more common in metal-forming processes. This type of flow is a consequence of high contact pressures, on the order of the material hardness [12], applied by an indenter (asperity/tool) at, or close to, a free surface. A basic understanding of the characteristics of surface plastic flow in sliding should be of value in analysing and controlling wear at metal interfaces, and in designing manufacturing processes to improve the functional characteristics of metal surfaces.

A model system often used to study unit asperity interactions in sliding contacts consists of a rigid, wedge-shaped indenter (asperity) pushed against a softer metal. This system, perhaps most relevant to abrasive wear and its variants [13,14], has been analysed using an influential family of slip-line field (SLF) models [15], complemented by experiments. Depending on the wedge incidence angle (θ) and friction, three modes of deformation were identified: formation of a prow (or wave) ahead of the sliding indenter (figure 1, right), generation of a detached prow and chip formation. In the prow regime, which corresponds to small incidence angles, no material removal is involved in one cycle of interaction. However, the accumulation of damage over many cycles of interaction leads to surface defects (e.g. cracks) and wear particles, with views differing over the extent to which the interaction is predominantly elastic [16], largely plastic [5,17] or elastic–plastic [6]. The detached prow and chip formation regimes occur at larger incidence angles and involve material removal within one or a few passes by fracture in the prow, or ductile cutting. It should be noted, however, that the incidence angles for chip formation are usually much greater than those typical of asperities in sliding metals. Particle formation in the adhesive wear regime has been described in terms of formation and rupture of junctions along the sliding interface [4,18].

Despite the importance of asperity deformation in wear, there has been little by way of direct observation of the asperity–metal interaction or of the surface flow field in sliding. The typical experimental approach, to paraphrase Tabor [19], has been to ‘investigate the resultants of the wear system at various stages and to attempt to reconstruct a picture of what is going on’. The problem with this ‘post-mortem’ examination is that evidence of the critical (unit) material removal events is masked or obliterated by subsequent events, leaving much room for conjecture [20].
To address this gap, we initiated an in situ study of deformation and flow at the mesoscale (approx. 100 µm–1 mm) in a sliding metal interface using the model system—a hard steel wedge (asperity, tool) sliding against annealed copper [21]. The wedge incidence angle ($\theta$) was varied between 5° and 30°, representing asperity angles on engineered (sliding) surfaces [22,23]. By combining high-speed imaging with image analysis (particle image velocimetry, PIV), important characteristics of the unconstrained plastic flow inherent to this system were elucidated. A key new observation was the formation of folds at the free surface of the copper, driven principally by grain-induced plastic instability. For a range of incidence angles, a series of protuberances or bumps developed on the polished surface ahead of the indenter, grew in amplitude and interacted with one another to form surface folds. Streaklines of the flow near the surface indicated a breakdown of simple laminar flow, revealing a flow pattern substantially different from that assumed in triboplastcity [5,6]. As a fold exited the wedge–Cu contact, it appeared to spawn a crack and/or a tear near the surface.

This work builds on these prior observations and shows how surface folds nucleate tears, cracks and wear particles in the wake of the wedge (asperity). This transformation of the fold is captured in real time using high-speed, in situ imaging of the wedge–specimen contact region. We establish a new mechanism of crack and particle formation by fold ‘splitting’ which has consequences for delamination wear. These observations are reinforced by scanning electron microscope (SEM), optical microscope and stylus profilometry characterization of the surfaces. PIV measurements of the flow and deformation field are also presented, providing insights into energy dissipation of relevance to sliding contact temperatures and surface damage in manufacturing processes.

2. Experimental set-up

The experimental system (figure 1) consisted of a workpiece (WP) in the form of a plate sliding against a hard steel wedge indenter (asperity) at speeds $V_o$ of up to 20 mm s$^{-1}$ under conditions of plane strain (two-dimensional) deformation [10,21]. The faces of the wedge indenter were ground smooth, with the direction of grinding on the wedge face in contact with the WP being perpendicular to the sliding direction and parallel to the indenter edge. The grinding ensured a sharp indenter edge (less than 10 µm) edge radius. It should be noted that the indenter rake angle (a term borrowed from metal cutting), as defined in figure 1, is equivalent to an asperity incidence angle ($\theta$), where $\theta = 90 + \alpha$; thus, larger incidence ($\theta$) angles correspond to smaller negative rake angles ($\alpha$) and more steeply inclined wedges. The rake angles were varied in the range of $-60^\circ$ to $-85^\circ$ ($\theta = 30^\circ$ to $5^\circ$) so as to be representative of asperity contacts in sliding. These angles are also typical of tool/die geometries used in surface conditioning and deformation processing. The depth ($h_o$) was set at 20 µm.

The WP material was commercially pure aluminium (Al 1100), with grain size ($D$) approximately 200 µm and in an initial annealed condition (Vickers hardness: 23 HV). The surface of the WP in contact with the wedge was given a final polish with 1200 grit SiC abrasive paper prior to the annealing. The root mean square roughness on the surface after the polishing, as measured by stylus profilometry, was approximately 0.1 µm. The sliding was carried out in a continuously lubricated environment (Mobol 1 for Al). Based on measurement of the forces in the sliding, the coefficient of friction ($\mu$) at the wedge–WP contact was estimated at approximately 0.10. In addition, there was no visible sign of metal transfer to the wedge, or built-up edge formation in the wedge–WP contact region, at the sliding conditions used in the experiments. Similar sliding experiments were also carried out with annealed OFHC copper ($D \sim 118$ µm), under both dry and lubricated conditions. But, because, the results presented here pertain mostly to Al, the specific conditions for Cu are cited only where necessary.

The flow of metal in the process zone was observed and photographed in situ using a high-speed imaging system (PCO dimax CMOS camera) coupled to an optical microscope assembly (Nikon Optiphot; figure 1). Quantitative details of the deformation and flow patterns were obtained by application of PIV to the image sequences [10,24]. In its basic form, PIV involves
the use of tracers or particles dispersed in the medium and then analysing the resulting flow field using digital image correlation [25,26]. The role of the particles in the present experiments was played by roughness features deliberately introduced onto the WP (side) surface being imaged by abrasion with 600 grit SiC paper. An optically transparent glass plate was used to constrain the imaged side so as to minimize out-of-plane flow of material during the sliding. The camera sensor had a full resolution of $2016 \times 2016$ pixel and physical size of $22.18 \times 22.18$ mm. Images could be recorded at up to 1279 fps using the full sensor area. Higher imaging speeds could be achieved by reducing the sensor area; for example, when the image size is $1296 \times 720$ pixel, framing rates of up to approximately 5000 fps are possible. PIV analysis of the image sequences was used to estimate displacement, velocity, strain and strain rate fields in the deformation zone [10,24]. Additionally, stream-, streak- and path-lines of flow, as in fluid flow, were obtained from the displacement and velocity fields [21] by the PIV; these were particularly useful for visualizing the flow features, and defect and particle formation.

The surface region of the WP was characterized using profilometry (Form Talysurf 50), optical microscopy and SEM. Stylus profilometry was used to measure the topography of the initial WP surface, the development of the prow region and the WP surface in the wake of the wedge (residual surface) after sliding. This enabled an assessment of development of various micro- and mesoscale features on the surfaces, including bump and prow sizes. Defect features and particles created by the sliding were analysed by optical microscopy and SEM of the surface regions and subsurface cross sections. These observations supplemented the in situ image data, while enabling a more complete picture of various facets of the sliding to be derived.

3. Results

The in situ imaging and the PIV analysis have revealed interesting, including hitherto little known, aspects of unconstrained plastic flow in sliding contact, and how a specific type of flow trigger the formation of folds, tears, cracks and particles.

(a) Laminar flow

Figure 2a shows one frame from a high-speed image sequence of sliding of Al with $\alpha = -75^\circ$ ($\theta = 15^\circ$). A prow of material of height $h_p$ is seen to build up ahead of the wedge, similar to that noted and analysed in prior sliding experiments [5,15,27] and deformation processing [28]. The superimposed streaklines in figure 2 indicate a smooth steady flow analogous to laminar fluid flow, and typical of what is usually assumed in SLF analysis of sliding and deformation processing [5,6,8,15]. The characteristic features of this pattern are the formation of small bumps—surface protuberances—ahead of the wedge, the growth in height of these bumps as they approach the wedge, and the subsequent occurrence of self-contacts between successive bumps that result in fold-like features (folds) on the surface.

(b) Disruption of laminar flow and surface folding

A qualitatively different flow pattern was observed at the surface when the sliding was carried out at smaller negative $\alpha$ (larger $\theta$). Figure 3a–d shows the evolving flow pattern in Al using four frames selected from a high-speed image sequence for $\alpha = -65^\circ$ ($\theta = 25^\circ$). A prow forms ahead of the wedge as before, with $h_p \sim D$. But an unusual, non-steady surface flow—with highly sinuous near-surface streakline pattern—is now seen to develop in the prow region. This is quite unlike the flow patterns commonly assumed (or predicted) in SLF or upper bound analysis of sliding and deformation processing [5,6,8,15]. The characteristic features of this pattern are the formation of small bumps—surface protruberances— ahead of the wedge, the growth in height of these bumps as they approach the wedge, and the subsequent occurrence of self-contacts between successive bumps that result in fold-like features (folds) on the surface.
The formation of specific bumps and their transformation into folds and, subsequently, defect features has been captured by the high-speed imaging. The green, red and yellow arrows in figure 3a show three bumps that have developed ahead of the wedge. With continued sliding, these bumps grow in height to approximately 50 µm in the prow region, see also figure 4 and related discussion, while coming closer together in the sliding direction and interacting to make self-contacts (folds), as shown at the white arrows in figure 3b. The evolution/propagation of these (two) folds through the contact region is shown in figure 3c, d. It is clear that fold formation precedes contact with the wedge face. But, a fold undergoes only minor changes as it traverses the wedge face in the contact region (figure 3c). A fold was, on occasion, observed to form by interaction of a single bump with the wedge face. The development of the folds is also well revealed in the changes in curvature (and minima) of the three to four streaklines immediately below the surface. The highly sinuous nature of the near-surface streaklines and the fold patterns, indicate that the flow is quite ‘non-laminar’ at this sliding condition, in contrast to figure 2. At sufficiently great distances (approx. 300 µm) below the surface, the streakline pattern is smooth and uniform indicating that the flow is again laminar (figure 3). A video of the bump formation and surface folding in aluminium is shown in the electronic supplementary material, movie S1.
Figure 4. Bumps in the prow region across the entire width of the contact as revealed by (a) SEM of the prow, contact region and vicinity, and (b) three-dimensional topography of the prow constructed from stylus profilometry (all dimensions in µm). ‘A’, ‘B’, ‘C’ show the initial WP, prow and residual surface, respectively. (c) Typical two-dimensional linescan profile across the prow (in the sliding direction) used to measure the bump height (δ). α = −65°, V = 5 mm s⁻¹, 1000 fps, aluminium WP, fluid: Mobil 1. SD, sliding direction of WP. (Online version in colour.)

The bumps are profuse in the prow region and occur over the entire width of contact, as seen in the SEM micrograph of the prow region (figure 4a, region B) and stylus profilometer traces (figure 4b). However, they are not present on the initial polished surface (region A) of the WP ahead of the wedge (figure 4a).

An assessment of the bump height was made using the profilometric traces. For this purpose, line scans in the sliding direction such as shown in figure 4c were made at different locations along the prow width. The maximum bump height in each line scan was measured. These heights were averaged over 30 line-scans to estimate δ; this value is taken as the bump height.

Figure 5 shows the variation of bump height (δ) with θ (or α); a steady increase of δ with increasing θ may be seen. Because δ likely scales with the grain size (D), see [21] and also discussion to follow, this height has also been shown in non-dimensional form (δ/D) in figure 5. Note that bumps and folds were observed in both dry and lubricated sliding.

The lateral dimensions of the bumps (figure 4) are very similar to the grain size (approx. 200 µm). This similarity is reinforced by our observation of slip markings confined within individual bumps. Additionally, SEM images of Cu samples with initial grain sizes in the range 30–250 µm, and lateral dimensions of bumps obtained by profilometry, reveal a strong correlation between bump size and grain size. Thus, it is clear that bump formation is deformation-induced, driven by the compressive field imposed by the wedge and the spatial heterogeneity in the flow properties of the metal polycrystal, consistent with prior observations and analysis in sliding of Cu [21]. A differential deformation at the surface, in fact, can also occur under a tensile stress field as with the ‘orange peel’ phenomenon observed in sheet metal forming [8]. However, the compressive field in the sliding is much more severe, leading to surface folds.

The surface strain field for the non-laminar sliding is quite heterogeneous (figure 6), with a lamellar pattern, made up of alternating regions of higher and lower ε, along the length of the WP. The regions of higher strain were typically coincident with the areas wherein folding was
observed. In addition, the ε levels (approx. 1.8–2.5) on the residual surface and strain gradients into the subsurface are much greater than for the laminar case.

(c) Surface defects and wear particles

As a fold exits the contact at the wedge tip, it is stretched and rotated (figure 3d), resulting in two types of surface defects. In some instances, the fold exits the wedge tip inclined almost parallel to the sliding direction and is seen as a crack on the residual surface (see at white arrows in figure 3d). The cracks thus produced are shallow and intersect the surface at very small (acute) angles. Often, these cracks are embedded in the subsurface and are not visible in a surface examination. Metallographic examination of the subsurface is, however, adequate to reveal these embedded cracks. In figure 3d, two folds may be seen near the wedge tip—one that has just exited the contact and the other that is about to exit.

In other instances, the bump region (ahead) of a fold, as it exits the wedge tip, ‘_splits’ or is torn off leaving behind a surface tear and a complementary crack-like feature—defect remnants of the fold—on the residual surface. The details of this fold splitting may be seen in the frames selected from an image sequence (figure 7), which focuses on the regions in and around the wedge tip. The curved dotted yellow line 12 in figure 7a is a fold arising from the contact of two bumps. The region 1234 (dotted yellow line) in figure 7 demarcates the bump that is immediately ahead of

Figure 5. Variation of bump height (δ, δ/D) with θ (or α) in aluminium. V = 5 mm s⁻¹, grain size (D) = 200 μm, sliding distance = 15 mm, fluid: Mobil 1. (Online version in colour.)

Figure 6. Surface strain field in the aluminium for α = −65°. The continuous arrows show regions of higher strain concentration on the surface, whereas the dashed line arrows point to less strained regions. V = 5 mm s⁻¹, 1000 fps, fluid: Mobil 1. SD, sliding direction of WP. (Online version in colour.)
Figure 7. Three frames with streaklines selected from a high-speed image sequence showing formation of tears and crack-like features on the aluminium surface. The dotted lines are drawn in manually to demarcate various features. A typical fold 12 is shown in (a). The point 3 in the bump region in (a) splits into points 3’ and 3 in (b) with a crack-like feature 2A134 developing. With further sliding, the other part of this bump 23’ A demarcated by a dotted line in (b) evolves into a tear 23’ in the wedge wake, as shown in (c). α = -60°, V = 5 mm s⁻¹, 1000 fps, fluid: Mobil 1. SD, sliding direction of WP. (Online version in colour.)

The fold. As sliding progresses and point 3 on this bump exits the wedge tip, a crack-like feature 2A134 (demarcated by dotted yellow line) is seen to develop, with point 3 splitting into 3 and 3’ (figure 7b). Note that part of this crack-like feature extending from point 2 to approximately point 1 is still underneath the wedge contact region. Furthermore, the crack-like feature as a whole is attached to the surface. This feature comprises of a crack 1A (dotted yellow line) that extends at an acute angle into the surface and is bounded by the bump remnant 43A1 (figure 7b). A significant stretching in the surface region of the bump, as it exits the contact, may also be noted, see for example the change in length of 34 between figure 7a,b.

The other remnant of the splitting—a tear 23’ outlined (enclosed) by the dotted white line—is seen partially emerging from the wedge tip region in figure 7c. Upon further sliding, this tear exits the contact essentially as a free particle. However, it was often observed that the flow of material in the vicinity of the wedge tip caused this type of ‘tear particle’ to attach itself loosely to the surface, the end result being a tear on the residual surface that is projecting upwards (figures 8a and 9). It points in a direction opposite to the direction in which the crack-like feature (figures 8b and 9) is oriented. Sometimes, the splitting of a fold was found to give rise to multiple tears. A video of folds splitting into tears and crack-like features is shown in the electronic supplementary material, movie S2.

Cracks, tears and particles were observed to form across the entire width of the sliding contact. Furthermore, the creation of the cracks and tears, and even some of the tear-initiated wear particles, occurred within one sliding pass.

The SEM micrograph in figure 8a shows a loosely attached tear in Al, whereas figure 8b shows the other remnant of the fold splitting, viz. the crack-like feature. Their opposing orientations are also clear in figure 8. Figure 9 is an SEM micrograph of similar tear and crack-like features in sliding of Cu. The co-location of the two features in this micrograph further highlights the complementary nature of the tear and crack-like features as remnants arising from splitting of a fold. Many of the tears and crack-like fold remnants were found to be only loosely attached to the surface, as evidenced by their removal from the surface during ultrasonic cleaning.
When a second sliding pass was made over the folded surface created by a prior pass, platelet-type particles were observed to detach from the surface. This is seen in figures 10 and 11 which highlight select frames from image sequences of the second pass sliding in Al and Cu, respectively. The frames in figure 10, with insets at higher magnification, show the opening up of a crack-like feature (white arrow, figure 10a, b) ahead of the advancing edge and its detachment as a platelet-type particle in figure 10c. A similar evolution of the crack-like features into platelet-type particles also occurs in Cu (figure 11), indicating that this delamination phenomenon is quite general to sliding metals. In the Cu, the detaching particles are seen to accumulate in the contact and move up the wedge face like a segmented chip (figure 11) common in metal cutting. Each segment of this chip is a platelet particle. The segments in the chip are only loosely attached to each other. The segmented chips were found to disintegrate easily upon light contact with a surface or on touching. The platelet-shaped particles typically formed in areas containing the defect remnants (tears, cracks) of folds; furthermore, they were observed along the entire width of the contact. The platelet particles had aspect ratios of approximately 12 and sizes corresponding to the widths of the fold remnants such as those shown in figures 8 and 9.

Figure 8. SEM micrographs showing (a) tear and (b) acute-angled crack-like feature on the residual surface. Note that the tear points in the direction of SD and the crack-like feature points in a direction opposite to SD. $\alpha = -60^\circ$, $V = 5 \text{ mm s}^{-1}$, aluminium, fluid: Mobil 1. SD, sliding direction of WP.

Figure 9. SEM micrograph showing co-located tear and crack-like feature on the residual surface in sliding of copper. $\alpha = -60^\circ$, $V = 1 \text{ mm s}^{-1}$, dry. SD, sliding direction of WP.
4. Discussion

The in situ study of metal flow around a sliding wedge has revealed a new mechanism of defect formation and of delamination wear at the mesoscale. These defects, in the form of cracks, tears and platelet particles, are a consequence of surface folding. Analysis of high-speed image sequences of the flow (figures 3 and 7) has revealed the key steps underlying the creation of the defect features. These are the formation of bumps ahead of the sliding wedge; the growth of these bumps followed by contacts between bumps, to produce self-contacts, i.e. folds, in the prow region that is bounded by the wedge–WP contact; and the conversion of the folds into acute-angled cracks and surface tears, when the folds exit the contact at the wedge tip. These steps can also be seen in the electronic supplementary material, movies S1 and S2.

The surface tears originate as platelet particles when the folded region exits the contact. But, these particles often attach themselves loosely to the residual surface as they exit the wedge tip owing to the nature of the material flow in this region (figures 8 and 9). The residual surface left behind after this sliding pass may be thought of as a pre-folded surface. When a second sliding pass is made by the wedge over this pre-folded surface, platelet-type wear particles are found to be created wherever crack and tear features—remnants of the prior sliding—are present on the surface (figures 10 and 11). The high-speed image sequences have also shown that a breakdown in the laminar nature of the flow and formation of vortex-like structures typically precede the fold...
development, consistent with earlier observations [21]. Cracks, tears and wear particles can thus form in as few as one to two sliding passes by the folding mechanism. Their formation does not involve any type of chip formation by cutting which typically occurs with the Al only for $\alpha > -50^\circ$ ($\theta > 40^\circ$); such incidence angles are beyond the usual range of asperity angles on surfaces. Note that chip formation has sometimes been proposed as a means for particle generation in abrasive wear [5,6,29].

Because the wedge represents a model asperity analogous to that present on surfaces, our work suggests a new mode of crack and particle formation (and delamination wear) that may be operative in sliding contacts. A single sliding pass of a suitably oriented asperity can produce a crack and tear, and even a particle, by surface folding, instead of crack nucleation by accumulation of plastic strains over many cycles [6,17]. Such cracks and tears will be removed in the subsequent sliding pass as wear particles. Indeed, the morphology and sizes of the crack features and particles observed herein bear a striking resemblance to those observed in a number of sliding (abrasive wear) studies, wherein ‘mechanisms’ as diverse as subsurface fatigue [16], delamination [17], low-cycle fatigue [7,15], ploughing [7,30] and cutting [6,15] have been highlighted as the origins of these defects. Some of the micrographs of the prow region in these studies also show features that could be interpreted as folds, as well as bumps resembling grains [31]. Separately, folds (‘sulci’) have been studied as entities of interest in their own right in other, non-plasticity contexts [32]. However, none of this prior work had suggested the folding-based mechanism for particle or crack generation. A more substantial comparison of our results with those of the prior work is hindered by insufficient data from these studies regarding material grain size, surface state, and spatial and temporal whereabouts of particle formation.

The observations and prior recent work [21] enable us to elucidate the principal factors influencing defect formation by folding. Certainly, breakdown of the laminar plastic flow is a key prerequisite for triggering fold formation and its derived effects at the mesoscale. Our prior work has shown that plastic fold formation by this type of flow disruption critically depends on a scale parameter ($\eta$), the ratio of the average grain size ($D$) to prow height ($h_p$). Larger values of $\eta$, such as $\eta \sim 1$ as in many of the current experiments with the Al, promote folding. Larger negative $\alpha$, i.e. smaller $\theta$, reduces the propensity for fold formation. Simulations incorporating grain level heterogeneity in flow properties have shown that there is a range of $\eta$ outside of which folding does not occur [21]. In alloys or composites, the $D$ value should correspond to a characteristic dimension of a specific phase, inhomogeneity or reinforcement. Our experiments have also shown that adequate material ductility is necessary for folding, and that greater levels of roughness on the initial WP surface enhance folding. It is likely that these effects can also be encapsulated via a modification of $\eta$. Because folding triggers the formation of cracks, tears and particles, $\eta$ is also likely the critical parameter controlling defect generation. A comprehensive study of this scale parameter, including grain size effects, on surface flow and folding is currently underway.

The strain field measurements (figures 2 and 6) have shown that the laminar flow condition results in a uniform distribution of subsurface strain in the wake of the wedge/asperity. By contrast, the subsurface strain field in the folding-dominated sliding is quite heterogeneous, with steep gradients. Such quantitative knowledge of the deformation should be of value in better characterizing heat sources in sliding contacts, and, by extension, in better estimating sliding contact temperatures and thermal stresses. These heat sources are to a large extent determined by the dissipation owing to plastic deformation and its spatial distribution in the WP near-surface region during the sliding [33]. The nature of the dissipation is dependent critically on the plastic strain and strain rate fields [34,35]. Similar observations may be made with regard to analysing and controlling surface damage, for example, phase transformations, residual stresses and microstructure changes, in manufacturing processes, wherein damage arises from the interactive effects of large strain deformation and high temperatures prevailing in the process/contact zones.

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1. See fig. 4.9 in [29]. This figure is a micrograph wherein bumps and self-contacts (fold-like features) are seen in the prow region ahead of a wedge.
2. The SEM pictures in figure 7ac [31] show bumps (resembling grains) on a surface ahead of erosion impacts.
[10,29,36,37]. These, as with sliding temperatures, are influenced significantly by the deformation fields prevailing in the WP near-surface region.

Besides sliding wear, the folding and associated defect formation has implications for areas ranging from surface generation to geology. Several processes based on repeated sliding and abrasion have been proposed for generating ultrafine- and nano-grained microstructures at surfaces [9,11]. This work shows that, absent careful selection of the tool rake angle, the surfaces thus produced would contain cracks and tears. Equally, importantly, the observations indicate that by suitably tailoring the initial microstructure of the WP material (e.g. ultrafine-grained) and the tool/die geometry, folding-induced defects in micromachining or surface conditioning processes may be reduced, thereby providing a means for improving the quality of surfaces in manufacturing. Lastly, the flow patterns and folding phenomena raise interesting questions as to what quantitative parallels can be drawn with structure and pattern formation in fluid dynamics, geology and granular matter [21,38–41].

5. Conclusion

The interaction between a model asperity and a metal in sliding contact has been studied, in situ, at high spatial and temporal resolution. Folds are observed to form at regular intervals on the metal surface ahead of the contact, the folding spawned by a breakdown of the laminar flow typically assumed in sliding analyses. A detailed examination has been made of how a fold traverses the contact and exits this region. Folds are shown to delaminate or split into tears, acute-angled cracks and platelet-type particles, as they emerge from the asperity tip. The details of fold splitting have been captured directly by the imaging. Wear, in the form of platelet-type particles detaching from the surface, is also observed when a second sliding pass is made over the folded surface created in a prior pass. Examination of the surfaces by microscopy and profilometry techniques has shown the folding to occur across the width of the sliding region, and provided additional data about the morphologies of the detaching particles, tears and cracks. These morphologies show close similarities with delamination features observed in a variety of sliding wear situations. The observations point to a new mechanism for delamination wear in sliding based on surface folding.

The phenomenon of particle and defect formation by folding appears to be quite general. Based on the observations and our prior work [21], we have outlined the key parameters controlling the folding and associated delamination wear. The need for incorporating this type of delamination mechanism into current wear models is clear from this work, even as we initiate a more extensive study into the effects of the key scale parameters: triggering folding and fold splitting. Surface folding and delamination have implications for a diversity of processes and phenomena, including wear, surface generation and conditioning processes, pattern formation in materials and geology, and fluid-like plastic flow in metals.

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