Wear behaviour and surface form evolution of a novel titanium carbide implanted surface under lubricated conditions

D I Fletcher, A Kapoor, K Steinhoff and N Schuleit
1Department of Mechanical Engineering, The University of Sheffield, UK
2Swiss Ammunition Enterprise Corporation, Altdorf, Switzerland

Abstract: Tribological behaviour (friction and wear) of heavily loaded lubricated surfaces is found to be influenced by the presence of very small scale surface textures. The Indirect Structuring process, which is described here, is a new method of surface texture production through implantation of a surface with wear-resistant regions. During use a surface texture is developed and maintained because, at a given wear rate, the wear-resistant regions can sustain higher contact pressures than can the substrate.

Indirect Structuring of a tool steel surface was carried out by laser implantation of the surface with titanium carbide implants, and rolling contact experiments were conducted under elastohydrodynamic and mixed-lubrication regimes. It was found that the indirect structuring process produces a surface structure which fulfils the design requirements for textured tool surfaces, and which is insensitive to the load applied to the surface. The mechanisms found to steer the development of the surface texture may be used to develop design methods for application of the Indirect Structuring process.

Keywords: surface texture, indirect structuring, wear mechanism

NOTATION

- $h_{\text{min}}$: minimum elastohydrodynamic oil-film thickness
- $R_a$: average roughness
- $R_q$: r.m.s. roughness
- $A$: ratio of $h_{\text{min}}$ to composite $R_q$ for both surfaces in contact

1 INTRODUCTION

Tribological behaviour (friction and wear) of heavily loaded lubricated surfaces is found to be influenced by the presence of very small scale (nanometric) surface textures. Although of very small size, surface textures are able to carry lubricant into heavily loaded contacts and to allow debris to pass out of these contacts without producing surface damage. The Indirect Structuring process is a newly developed method of surface texture production, and this is described below.

One of the widest applications of textured surfaces is in the forming of sheet metals where tribological considerations are often combined with the requirement to produce a certain paint appearance on the finished component, e.g. on a car body panel. Although the Indirect Structuring process has a variety of applications, the production of textured sheet metals is therefore taken as an example, and the performance of the surface is investigated in this context.

1.1 Surface texturing

Sheet metals used for products manufactured by forming operations (e.g. car body panels) are typically produced by a cold-rolling process during which sheet surface texture is produced by transfer of roll surface texture. Steinhoff et al. provided design guidance for forming tool or roll surface textures, the essence of which is that a uniformly distributed array of surface features of approximately uniform height should exist so that the required channels for lubricants and debris cover the whole of the surface of the tool. To be effective these channels need be only in the submicrometre height range and should not greatly exceed this height so that interlocking of the tool and product surface is avoided. Such interlocking of textured surfaces has been described by Sheu et al.

Traditionally a very basic forming tool surface texture has been created by shot blasting the tool surface. More recently surface textures have been created by processes...
such as Lasertex [14–16] or electron-beam texturing [17–19]. However, it has been found that these techniques are unable to fulfil both the requirements of the steel industry regarding production characteristics during cold rolling and the requirements on formability and paint quality of the sheet, coming primarily from the automotive industry. The principal reasons for this are insufficient uniformity of surface texture and poor wear resistance of the surface features. The underlying cause of poor wear resistance is that, following texturing, the wear properties of the surface remain virtually uniform at all points. Raised areas of the surface, which support a larger proportion of the applied loads than do the lower areas of the surface, wear more rapidly than the surrounding material and a steady state is reached in which load is uniformly distributed and the surface texture has been removed.

A possible solution to the removal of texture by wear would be to coat the raised areas of the surface with a wear-resistant coating. However, this would be a process in addition to the creation of the texture. More useful would be the implantation of the surface with wear-resistant regions of substantial depth so that a texture would develop through wear of the surface, with the wear-resistant implants being left standing above the surrounding material.

1.2 Indirect Structuring

A process by which wear-resistant regions may be formed on a surface is the Indirect Structuring process [11, 20] which relies on surface thermal implantation with metal carbide particles. For a steel surface implanted with titanium carbide (TiC) particles, the hardness within the treated regions is typically twice that of the underlying material. Shot blasting and subsequent polishing prior to use of the surface wears the steel substrate at a rate higher than that of the carbide implants and therefore produces a surface texture. The process is illustrated schematically in Figs 1a to c. The wear-resistant regions produced by the process are deep enough (Fig. 1c) that they can sustain large amounts of surface wear without losing effectiveness.

During use, when the surface is worn by contact with the product sheet rather than by shot blasting, a steady state surface texture develops, which is dependent on a dynamic equilibrium of wear and load redistribution between the substrate and the implants. This is possible because the difference between the surface heights of an implant and its surrounding substrate causes the contact load to be distributed such that the wear rates (i.e., rate of surface height reduction) are equal for both. For example, excessive wear of the substrate surrounding an implant effectively increases the implant height, causing the implant to support an increased proportion of the contact load. This redistribution of load will accelerate the wear of the implant and decrease that of the substrate, leading to eventual equilibrium of surface form and load distribution for which the wear rates of the implant and substrate are equal. Although a texture could also be developed by this mechanism rather than by shot blasting of a newly treated surface, shot blasting has two key advantages. First, it produces a surface form similar to that which develops in the steady state, thereby minimizing any running-in period. Second, it produces compressive residual stresses close to the surface, and these stresses will help to suppress rolling contact fatigue failure of the surface.

To fulfil the textured tool design requirements [11] the surface must have certain features:

1. The height of the implants above the substrate must be maintained in a reasonably narrow band to avoid localized high contact pressures.
2. The mean implant height must be sufficient to allow the channels formed by the surface texture to retain lubricant and debris, but interlocking of the tool and product should not occur.
3. Load variation may be expected both due to process control and due to accidental overloads. Although the surface is produced and maintained by a wear process, which is contact load dependent, the mean implant height and range of implant heights should ideally show little response to a change in the applied load (Fig. 2).
4. The mechanisms of surface texture formation must be insensitive to minor differences between the implants. Such minor differences are unavoidable in a process which relies on the mixing of molten metal and carbide particles, and variation in the implant diameters, depths and composition will always exist, although on a macroscopic scale all the implants appear to be identical. The greater the tolerance of these differences, the less tightly controlled (and therefore less expensive) need be the production of the surfaces.

This paper describes the initial stages in the investigation of the Indirect Structuring technique. An experimental method by which wear and load sensitivity of an indirectly structured surface may be tested is described, and results are presented, illustrating the effect on the treated surface of a step load increase to five times its initial value. It was found that the surface did respond to the increase in applied load, but the surface texture was preserved. The maintenance of surface texture was found to be tolerant of minor differences between the implants studied. Wear of the surface was found to be very mild, and a possible wear mechanism is proposed to explain the observations.

2 EXPERIMENTS

2.1 Rolling contact testing

To maintain close control over the experimental conditions it was decided to use the small scale lubricated twin-disc rolling contact test method in which a treated disc (non-driven) ran in line contact with an untreated counterdisc.
Fig. 1  The Indirect Structuring process. (a) A laser is used to melt the tool surface locally and metal carbide particles are sprayed into the melting zone, forming wear-resistant regions on the surface. The laser or surface is moved to treat the surface at an array of points. (b) Schematic representation of the melting zone during metal carbide implantation. (c) Following cooling, shot blasting and polishing, the surface is covered by an array of implants with this typical cross-section. Although the top of the implant is above the steel substrate, the height difference between the components is small relative to the overall dimensions of the implant. (d) The implant distribution used for the current test. The implants were most closely packed in the direction parallel to the axis of the disc. (e) A reflected light intensity plot produced using an NT2000 interferometer. The plot shows a single implant (indicated by a dashed circle) and also shows small carbide particles protruding from the surface of the implant, an example of which is indicated by the small solid circle.
Both discs had an outside diameter of 76 mm and were 15 mm wide. The lubricating oil (Shell Turbo 68) was drip fed into the contact between the discs at a rate sufficient to maintain an excess of lubricant at the contact entry. A normal load was applied to the discs using a mass on a loading arm attached to the bearing housing of the treated disc.

To reveal the sensitivity of the surface texture to the applied load the test was conducted in two stages using a single specimen and counterface. These stages were conducted at a low and a high load respectively and will be referred to as stages I and II. Details of the contact conditions for each stage of the test are given in Table 1, assuming that both the treated and the counterface discs have the properties of the substrate steel (Table 2) and have smooth surfaces [22–24]. The calculations show that stage I took place under elastohydrodynamic lubrication conditions \(3 < \lambda < 10\), and stage II with mixed lubrication \(1 < \lambda < 5\) [25].

Stage I ran for 111 100 cycles and stage II for 111 260 cycles. Measurements were taken at 0, 100, 1000, 10 000 and 100 000 cycles in stage I, and at 0, 10, 50, 200, 1000, 10 000 and 100 000 cycles in stage II.

2.2 Materials

The disc specimen had a steel substrate and was laser implanted with TiC using a triangular implant distribution, with one of the packing directions parallel to the disc axis. Implants were separated by approximately 40 \(\mu\)m of substrate material in the packing direction parallel to the disc axis and by approximately 100 \(\mu\)m in the other packing directions (Fig. 1d). The mechanical properties of the constituent materials of the specimens are given in Table 2, although the material properties within and surrounding the implants are dependent on heating and subsequent cooling during the laser surface treatment, and the ratio of steel to TiC at a particular position. The counterface disc was of the same steel as the substrate of the treated disc.

2.3 Measurements

The tangential load at the contact of the discs was measured using calibrated strain gauges fixed to the bearing housing supporting the non-treated disc. Data were recorded using a computer-based data acquisition system. The coefficient of friction was determined from the ratio of the tangential to the normal load transmitted by the contact.

A white-light interferometer (WYKO NT2000) was used to examine the treated disc prior to testing and at each interruption of the test. One implant was examined at each of eight positions at 45° intervals around the circumference of the disc, near the centre of the disc track. Relocation of the disc ensured that the same set of implants was examined at each stage of the experiment. The interferometer measures both the intensity of light reflected from the surface and the surface height, with a vertical height resolution of 0.1 nm.

A feature of the surface implants was that TiC particles protruded from the surface of the implants, although the particles were typically no more than 1 \(\mu\)m above the surrounding treated region. The measurements made during the experiments were therefore chosen to describe the wear of the specimen surface, taking into account both the protruding carbides and the underlying form of the surface. Interestingly it was noted that, following wear,
implanted surface was similar to the surface of a road or pavement in which wear causes embedded stones to become raised above the relatively soft surrounding asphalt.

### 2.3.1 Implant diameter

During preliminary tests it was found that the implants wore so that the interface of the implant and surrounding substrate material could not be identified from the surface height data, i.e. there was no detectable lip or ridge at the edge of the implants. However, using the reflected light intensity data, also collected by the interferometer, it was found that the implants were clearly revealed due to the difference in the amount of light reflected by the implants and the substrate (Fig. 1e, which also shows the carbides that protruded from the implant).

The variation in reflected light intensity was thought to correlate with the local slopes of the surface, some indication of which is given by the roughness, rather than with bulk surface form. Of the implant and the substrate the implant was always found to have a lower surface roughness, and at the start of the test typical average roughness measurements for the implants and the substrate gave $R_a$ equal to 12 nm and just under 85 nm respectively. Diameter measurements were found to be subject to an uncertainty of approximately ±1.5 per cent. This was primarily due to the gradual change in roughness at the interface of the implants and the substrate, which was thought to be due to a gradient in the material properties in this region. At the start of the test the mean implant diameter for the eight observed implants was 0.446 mm, with the largest and smallest measuring 0.462 and 0.431 mm respectively.

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### Table 1  Applied loads and contact conditions

<table>
<thead>
<tr>
<th></th>
<th>Stage I</th>
<th>Stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (N)</td>
<td>200</td>
<td>1000</td>
</tr>
<tr>
<td>Speed (r/min)</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>Maximum Hertzian contact pressure (MPa)</td>
<td>157</td>
<td>350</td>
</tr>
<tr>
<td>Hertzian contact half-width ($\mu$m)</td>
<td>54</td>
<td>121</td>
</tr>
<tr>
<td>R.m.s. surface roughness $R_q$ of treated surface ($\mu$m)</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>Minimum elastohydrodynamic oil-film thickness $h_{min}$ ($\mu$m)</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Lambda ratio $A^*$</td>
<td>4.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>

*The counterface r.m.s. surface roughness was 0.4 $\mu$m in both cases.

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### Table 2  Material properties of the constituents of the disc

<table>
<thead>
<tr>
<th></th>
<th>Tool steel - code 1.2601</th>
<th>TiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>200</td>
<td>450</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.3</td>
<td>0.19</td>
</tr>
<tr>
<td>Vickers hardness (HV)</td>
<td>280$^*$</td>
<td>320$^{100}$</td>
</tr>
</tbody>
</table>

$^*$50 kg load.

$^{100}$100 g load.

The lack of a reliable datum point on the surface made absolute height measurements impossible; therefore the implant height was defined as the difference between the height of the peak of an implant (relative to an arbitrary datum) and the substrate level measured relative to the same datum. The use of relative implant height (RIH) was thought to give a good indication of the size of the channels in which lubricants and debris would be present during use of the surface and was therefore relevant to the performance of the surface.

The height of the implant peaks was taken as an average height over an area of 0.035 mm$^2$ at the top of each implant examined and for the substrate over an area of 0.070 mm$^2$ covering the deepest regions between neighbouring implants. These areas were large enough to include multiple asperities and therefore to decouple the height measurements from modifications of the surface roughness. In the centre of the implants the surface was found to have approximately 16 000 zero crossing points (i.e. asperities) per square millimetre; thus the area examined would be expected to include around 560 asperities. For the substrate the corresponding values were 4500 asperities per square millimetre and around 315 asperities within the area examined. The uncertainty on the height measurements was estimated to be ±2 per cent, resulting from slight differences between the position on the implants at which measurements were taken at each stage of the test.

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### 2.3.2 Relative implant height

The height of the implant peaks was taken as an average height over an area of 0.035 mm$^2$ at the top of each implant examined and for the substrate over an area of 0.070 mm$^2$ covering the deepest regions between neighbouring implants. These areas were large enough to include multiple asperities and therefore to decouple the height measurements from modifications of the surface roughness. In the centre of the implants the surface was found to have approximately 16 000 zero crossing points (i.e. asperities) per square millimetre; thus the area examined would be expected to include around 560 asperities. For the substrate the corresponding values were 4500 asperities per square millimetre and around 315 asperities within the area examined. The uncertainty on the height measurements was estimated to be ±2 per cent, resulting from slight differences between the position on the implants at which measurements were taken at each stage of the test.

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### 2.3.3 Implant and substrate surface roughness

The average roughness ($R_a$) for the whole surface, including both the implants and the substrate, gives an indication of the overall state of the surface, and results are presented for the start of each stage of the test and the end of the test. However, although $R_a$ could be measured for any region of the surface, the measurements are most useful if they can be linked to a particular surface feature. For this reason, measurements for each interval of the test are presented only from well within the implanted region, avoiding protruding carbides, and for the substrate steel between the implants.
3 RESULTS

3.1 Implant diameters

Figure 4 shows the variation in implant diameters during the test and Table 3 gives the mean diameter values for each stage of the test. The diameters showed some contradictory variations during both stages I and II; however, the changes measured were in many cases within the ±1.5 per cent uncertainty to be expected in these readings. The mean implant diameter for all eight observed implants was reduced during each increment of the test, and at the end of stage I had been reduced by approximately 2 per cent. By the end of stage II the mean diameter had been reduced by just over 5 per cent of its initial value. These reductions exceeded the uncertainty present in the readings, and therefore indicate a true reduction in the implant diameter. Because the implant form is conical (Fig. 1c), reduction in the implant diameter at the surface would be expected following wear, and the diameter reductions are used to estimate a surface wear rate in Section 4.

Fig. 4 Variation in the implant diameter for each of the eight implants observed: (a) variation throughout the test; (b) detail of changes at the start of stage I; (c) detail of changes at the start of stage II
3.2 Relative implant height

Figure 5 shows the results of RIH measurements over the whole test, including both stages I and II. An increase in the RIH indicates that the substrate steel wore at a rate exceeding that at the top of the implant, while a decrease in the RIH indicates more rapid wear at the implant top than of the substrate. From Figs 5b and c it can be seen that, although the RIH was changing throughout the test, there is little consistency between the variations which took place at each implant. A possible source of these inconsistencies, which were not thought to be solely due to uncertainties in the measurements, was the variation between the material properties and sizes of the implants, and this is discussed in Section 4. Throughout the whole test the RIHs remained within a band of less than ±15 per cent of the mean RIH.

Since no trend in the RIH could be identified for either stage of the test, it was decided to consider all the readings in each stage together to reveal differences between the stages. Taking the whole of stage I the RIH has a mean value of 1.29 μm with a standard deviation of 0.10 μm. The corresponding values for stage II were 1.30 μm and 0.09 μm; therefore the increase in load during the second stage of the test can be seen to have had almost no effect on either the mean RIH or the distribution of the measurements about this mean value. Mean RIH readings for each interval of the test are given in Table 3.

3.3 Implant surface roughness

The implant surface roughness was very low throughout the test (the mean implant Rₐ was 11.9 nm at the start of the test) but there was a clear difference between the values in stages I and II. Figure 6 shows that, following load application, at the start of stages I and II the implant surface roughness first decreased and then increased; the drop was only marginal during stage I but was dramatic during stage II. The increase after this initial drop was substantial during stage I but only marginal in stage II.

Mean values for each interval of the test are given in Table 3.

3.4 Substrate surface roughness

Figure 7 reveals that the roughness of the substrate was modified during the experiment, although its variation was not proportional to the variation in the implant roughness. The substrate was in all cases rougher than the implant surfaces, averaging 54.3 nm at the start of the test.

3.5 Overall roughness and bearing area curves

Considering the whole surface, including the implants and the substrate, the mean roughness Rₐ for all eight regions observed at the start of the test was just over 192 nm. At the end of stage I this had risen to 209 nm but at the end of the test was 181 nm. Bearing area curves and surface height histograms were calculated; however, these showed that changes in the surface were very small and no trend could be identified.

3.6 Coefficient of friction

The variation in the coefficient of friction during the test is presented in Fig. 8, and comparison with Fig. 6 shows a strong correlation with the implant surface roughness measurements. At the start of the test the coefficient of friction was very low, but it increased throughout stage I, reaching 0.035 at the end of this stage. The increase in the contact load and consequent reduction in the lubricant film thickness in stage II of the test was accompanied by a dramatic reduction in the coefficient of friction, to less than 0.002 after the first 10 cycles of contact. The values continued to fall until 111 360 cycles and then increased slightly to reach just over 0.003 at the end of the test.

The values of the friction coefficient support calculations showing that the lubrication regime was elastohydrodynamic in stage I but mixed in stage II (Table 1). A reduction in the friction coefficient is expected with a

<table>
<thead>
<tr>
<th>Number of cycles</th>
<th>Stage</th>
<th>Mean implant diameter (μm)</th>
<th>Mean relative implant height (nm)</th>
<th>Mean implant surface roughness Rₐ (nm)</th>
<th>Mean substrate surface roughness Rₐ (nm)</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>I</td>
<td>446.3</td>
<td>1298</td>
<td>11.9</td>
<td>54.3</td>
</tr>
<tr>
<td>100</td>
<td>I</td>
<td>445.3</td>
<td>1306</td>
<td>9.6</td>
<td>54.6</td>
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<tr>
<td>1100</td>
<td>I</td>
<td>444.1</td>
<td>1288</td>
<td>15.6</td>
<td>56.5</td>
</tr>
<tr>
<td>111 100</td>
<td>I</td>
<td>437.0</td>
<td>1309</td>
<td>14.9</td>
<td>57.9</td>
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<tr>
<td>111 110</td>
<td>II</td>
<td>432.9</td>
<td>1322</td>
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<tr>
<td>111 160</td>
<td>II</td>
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<td>8.2</td>
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<td>422.2</td>
<td>1312</td>
<td>8.3</td>
<td>60.1</td>
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reduction in film thickness until the boundary lubrication regime is reached at \( \lambda < 1 \) \[24, 25\].

**4 DISCUSSION**

The Indirectly Structured surface tested fulfils the design requirements for a textured surface which were summarized in Section 1.2. Despite a load increase to five times its initial value and a corresponding change in the lubrication regime the surface maintained a form capable of retaining lubricant and debris in channels approximately 1 \( \mu \)m deep surrounded by raised regions of approximately equal height. The reduction in the diameter of the implants and surface roughness modification of both the implants and their surrounding substrate indicates that the surface was undergoing wear (i.e. the surface form was not retained
simply because the surface did not wear). However, the changes observed were small and indicate that the wear was of a very mild form. This would be expected for a textured surface with lubricant trapping properties running under elastohydrodynamic conditions.

Although no datum point was present on the surface, an upper bound estimate of the total wear that occurred during the test may be made using the implant diameter measurements. From the cross-section of a typical implant (Fig. 1c) it can be seen that the implants were conical with a semicone angle of approximately 20°. The mean implant diameter reduced by just over 24 μm during the 222 360 cycles of the test. If the uncertainty of ±1.5 per cent (approximately ±6 μm) present on the implant diameter measurements is included, then the diameter reduction becomes between 12 and 36 μm. Using trigonometry to convert the diameter reduction to a reduction in the surface level shows that surface level was reduced by between 16.5 and 49.5 μm, or between 0.07 and 0.22 nm per contact cycle.

Williams et al. [24] reported that mild wear is characterized by the production of wear debris typically around 100 nm in size (diameter) and it is therefore thought

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**Fig. 6** Implant roughness $R_a$ results: (a) variation throughout the test; (b) detail of changes at the start of stage I; (c) detail of changes at the start of stage II
that wear took place by the loss of discrete particles rather than by a uniform reduction in the surface height with each contact cycle. This implies that the number of discrete wear ‘events’ at any point on the surface must have been far fewer than the number of contact cycles. The discrete nature of the wear process may have affected some of the measurements taken from the surface, and this is described below.

Figure 9 describes the discrete wear process in terms of surface height modification. The mean surface height of regions A and B is shown by thick solid curves, and the height of points a and b is indicated by the thin curves. The height difference between regions A and B of the surface during shot blasting and polishing is represented by $H_0$ to the left of Fig. 9. Following shot blasting and polishing, this height reaches a steady state $H_1$ at time $t_1$.

The height $h_1$ is the height difference between points a and b just before a wear event takes place at b. Following this wear event the relative height of points a and b increases to $h_2$, but a wear event then takes place at a; therefore the subsequent height reading $h_3$ is less than $h_2$. For the current surface the thicknesses of the wear debris...
from the implant and substrate would be expected to be different, and wear events would be unlikely to take place simultaneously in both regions; thus the height difference between these regions would fluctuate about a mean value, as shown in Fig. 9.

Since the wear debris is not produced by removal of a layer of uniform thickness from the surface, the roughness left in the area which loses material may be different from the original roughness. Some of the variations in the roughness may be attributable to this effect. However, it

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**Fig. 8** Variation in the coefficient of friction with number of contact cycles throughout the test

**Fig. 9** The discrete wear model. The surface height of an implant and the substrate is measured over regions A and B, and at points a and b (see inset). Prior to shot blasting and polishing, the height of region A relative to B is zero. Following disc preparation the height difference between regions A and B becomes constant \(H_1 = H_2\); however, the relative height of the points a and b varies due to discrete wear events, indicated schematically by the heights \(h_1\) to \(h_3\). The absolute heights of both surfaces decrease due to wear.
must be remembered that the area over which measurements of roughness and RIH were taken has an averaging effect. As the measurement area increases in relation to the debris size, the fluctuations in the measurements become fewer.

4.1 Load distribution and surface form evolution

Figure 10a shows a schematic representation of the implanted surface and the counterface. The load supported by the surface determines the mean separation. During sliding of the counterface over the treated surface, the counterface asperities make contact with both the implants and the substrate surrounding them. As some asperities come into contact, others lose contact and the mean separation of the surfaces remains constant.

Despite being very smooth (r.m.s. roughness $R_q$ of $0.4 \, \mu m$ and $0.58 \, \mu m$ at the start of the test for the counterface and implanted surface respectively) at any time the counterface and implanted surface will each have surface features of various heights and this variation is shown in Fig. 10a by the probability distribution functions $\phi_1(z)$ and $\phi_2(z)$ respectively; $\phi_2(z)$ is steeper than $\phi_1(z)$ because the variance in the laser-treated implant heights is small relative to the variance of heights in an untreated surface. Moreover, considering two implants of slightly different heights, curves A and B in Fig. 10a, the higher implant will experience relatively more asperity contacts and in response it may be expected to reduce its height, narrowing the distribution $\phi_2(z)$, a self-generating feature that is naturally desirable.

Considering just a single implant, Fig. 10b shows a typical implant and its surrounding substrate with a rough counterface sliding over them. For a given mean separation of the surfaces the proportions of the counterface asperities making contact with the substrate and with the implant are shown by the shaded areas. Clearly for a given mean separation of the surfaces a large value of the RIH means that relatively few asperities make contact with the substrate. Physically, the large RIH shows that the implant stands well above the substrate and will protect it by pushing away the surface of the counterface. Rolling or sliding under these conditions will lead to more wear at the top of the implant than of the surrounding substrate, and changes observed in roughness match this hypothesis very well.

Figure 5 shows that, throughout the tests, implant 8 had one of the largest relative heights, and Fig. 7 shows that the substrate roughness measured close to this implant was low and was altered only slightly by the application of load at the start of stages I and II. Conversely, implant 5 had a smaller relative height and a larger substrate roughness, and this roughness showed a large response to the application of load to the surface at the start of stages I and II.

Although the model shown in Fig. 10b is for a particular RIH (i.e. implant height relative to the substrate immediately surrounding it), it is important to remember that the proportion of contact load (or the number of asperity contacts) that the implant and substrate support actually determines the RIH. This height is modified by wear so that the wear rates of the implant and its

![Fig. 10](image)

Fig. 10 Asperity contact model: (a) multi-implant model; (b) single-implant model. Diagrams not to scale
surrounding substrate are equal in the steady state. It is thought that the maintenance of this equilibrium at each implant was one factor which limited the range of RIHs during stages I and II of the experiment to within a band of less than ±15 per cent of the mean RIH. An additional factor limiting this range is thought to be that all the implants were of similar heights relative to one another (i.e. they had the predicted narrow probability distribution function) and each therefore experienced a similar degree of contact with the counterface. However, since absolute heights could not be measured reliably during the experiment, this could not be confirmed.

Considering the variety of factors controlling implant behaviour, it should not be expected that all the implants will undergo similar modifications at any one time, although they should share longer-term trends for maintaining approximately equal absolute heights and approximately equal heights relative to their surrounding substrate. Although the explanations of the observed behaviour that are discussed above are plausible, they require further investigation before firm conclusions can be drawn. To develop a design method for implanted surfaces capable of predicting the implant height distribution and wear behaviour for particular load and contact conditions, it is thought that two interacting strands of further investigation are required. First, it is necessary to investigate the wear of a single implant in greater detail so that the individual wear events can be quantified and the modification of implant form, rather than just the relative height, can be examined. Second, it is necessary to model how the load applied to the surface is distributed among a population of implants of slightly varying heights, geometry and mechanical properties.

5 CONCLUSIONS

The Indirect Structuring process of surface texture production through surface implantation with wear-resistant regions has been described. An example of its application is in the production of a forming tool surface texture, and its ability to produce such a texture has been demonstrated on a small-scale specimen. Rolling contact experiments conducted under elastohydrodynamic and mixed-lubrication regimes have revealed that a surface treated using the process is able to maintain a surface structure that fulfils the design requirements for textured tool surfaces and that is insensitive to the load applied to the surface.

Wear of the surface was described as a discrete process in which the number of wear events at a given point was far fewer than the number of contact cycles. The summation of the discrete wear events was thought to maintain an equilibrium between the surface height and the contact pressure supported by each point on the surface. It is through this mechanism that surface texture is maintained because the wear-resistant implanted regions can sustain higher contact pressures than the substrate for a given wear rate. Further work is required to investigate the wear processes and evolution of surface structure that have been predicted following the experimental work reported here.

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