# THE EFFECT OF SURFACE PRODUCTION TECHNIQUES ON THE TRIBOLOGICAL BEHAVIOUR OF FLUID LUBRICANTS

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## ABSTRACT

Gears and bearings are often designed specifically for use in spacecraft mechanisms, and when doing so careful consideration must be given to their tribological surfaces. When preparing engineering drawings, the $R_a$ of the component is usually the only aspect of the surface finish which is specified. However, several other surface parameters exist, which may differ when the same $R_a$ is achieved through multiple finishing techniques. ESTL has conducted several investigations into the significance of these parameters.

These activities have found that for larger $R_a$ values (>0.15, as are typically used in gears) the behaviour of fluid lubricated surfaces is similar, regardless of the finishing method employed. However, for lower $R_a$ values (<0.1, as is typically used in bearings) the behaviour is governed by additional surface parameters, with differing finishing techniques providing different mid-test friction and lifetimes

## 1. BACKGROUND

Previous studies into the effect of surface finish on the in-vacuo performance of space lubricants have primarily focussed on solid lubricants, such as $MoS_2$ thin film coatings [1]. These have shown that the lifetime and durability of the lubricant layer can reduce with increasing surface roughness ($R_a$). This has been explained as being due to a reduction in the true contacting surface area (and hence increasing the contact stress), which results in a shorter life. However, to the authors knowledge, no studies exist to determine the influence of $R_a$ on in-vacuo fluid lubricated surfaces. In addition to this, the previous study focuses specifically on the surface roughness, excluding the influence of additional surface parameters. These parameters are known to differ across surface finishing techniques, all of which can produce similar $R_a$ values [2]. The parameters of relevance for this study were the arithmetic mean square height ($S_a$), the root mean height ($S_q$), the skewness ($S_{sk}$), the kurtosis ($S_{ku}$) and the isotropy (from $S_{tr}$). These parameters are defined in Tab. 1.

The chosen surface finishing techniques include lapping, superfinishing, EDM and grinding. These are detailed further in Tab. 2 [2].

**Table 1. Descriptions of different surface parameters included in this study**

| Parameter | Definition |
|---|---|
| $S_a$ | $S_a = \sqrt{\frac{1}{A}\iint_A \lvert Z(x,y)\rvert dxdy}$ (1) |
| $S_q$ | $S_q = \sqrt{\frac{1}{A}\iint_A Z(x,y)dxdy}$ (2) |
| $S_{sk}$ | $S_{sk} = \frac{1}{{S_q}^3}\frac{1}{A}\iint_A Z^3(x,y)dxdy$ (3) |
| $S_{ku}$ | $S_{ku} = \frac{1}{{S_q}^4}\frac{1}{A}\iint_A Z^4(x,y)dxdy$ (4) |
| Isotropy ($S_{tr}$ represented as a %) | $S_{tr} = \frac{min\sqrt{tx^2+ty^2}}{max\sqrt{tx^2+ty^2}}$ (5) |

**Table 2. Descriptions of different surface finishing techniques**

| Technique | Description |
|---|---|
| Lapping | Using suspended angular particles to abrade the surface (typically in a slurry) |
| Superfinishing | A low temperature, low stock removal method, typically used as a after course grinding to achieve a cross-hatched low $R_a$ |
| EDM | Asperities are removed by an electrical discharge stimulated by having the workpiece and the electrode being oppositely charged |
| Grinding | Using fixed angular particles to abrade the surface |

## 2. TEST EQUIPMENT

The morphological aspects of this study were analysed using an ST400 Profilometer with chromatic confocal optical technology (from NANOVEA). The surface parameters were determined from a scan of area 500µm by 500µm, which had been exposed to a computational plane fit (to remove waviness and other form errors).

Chromatic confocal optical profilometry works by creating a colour spectrum, using a lens to diffract the white light. The light reflected by the surface corresponds to the frequency of the specific region of the spectrum, that is bisected by the surface, Fig 1.

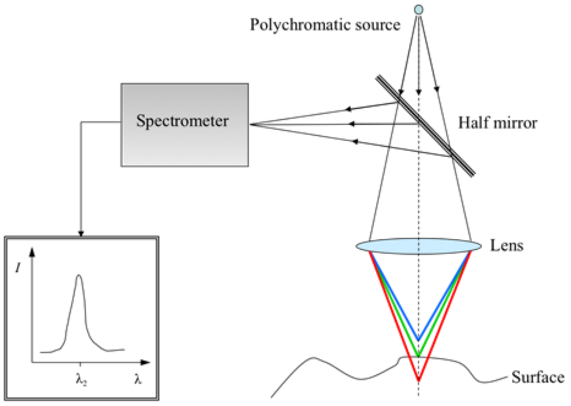


**Figure 1. The process of chromatic confocal optical profilometry [3]**

The tribological aspects of this test were conducted using a spiral orbit tribometer (SOT).

The SOT is essentially a thrust bearing, with an individual ball held between two interchangeable flat plates, located within a vacuum chamber. A load is applied to the top plate via a spring-loaded linear translator. The lower plate rotates via a motor located outside the chamber, causing the ball to move in a spiral path.

This configuration causes the ball to spiral outwards, and a fixed guide plate is positioned to keep the ball within the flat plates and to produce a repeatable orbit. A force transducer behind the guide plate measures the force exerted by the ball onto the guide plate. From this a friction coefficient value is found, once per orbit.

The arrangement of the SOT allows the ball to experience rolling, sliding and pivoting – all motions experienced by a ball in an angular contact bearing. This allows for a more representative testing of a lubricant than conventional pin-on-disc testing, which only recreates sliding motion.

The PFPE oil Fomblin Z25 was chosen as a lubricant in this study as it has been tested extensively on the SOT (under vacuum) and thus a large quantity of comparison data exists.

## 3. METHODOLOGY

The surfaces were characterised both prior to and after tribological testing and the $S_a$, $S_q$, $S_{ku}$, $S_{sk}$, and isotropy were determined.

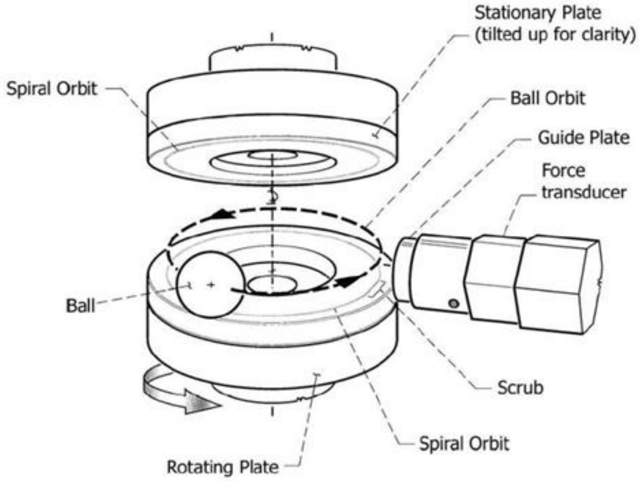


**Figure 2. Internal arrangement of the SOT**

The tribological testing was conducted using the experimental parameters detailed in Tab. 3. All the experimental parameters were held constant, with only the surface finishing method differing between test items [4].

**Table 3. A summary of the test conditions used for the tribological aspects of the study**

| **Parameter** | **Value/Detail** |
|---|---|
| Peak contact stress | 2.25 GPa |
| Rotational ball velocity | 100RPM |
| Ball and plate material | 440C steel |
| Test environment | $<1.3\text{x}10^{-6}$ mbar |
| Temperature | 23°C ± 3°C |
| Failure condition | Friction coefficient ≥ 0.28 (for 3 consecutive orbits) |

## 4. RESULTS

### Pre-Test Surface Characterisation

Profilometry images were taken in the wear scar region, and surface parameters were quantified. The pre-test surface parameters are summarised in tab. 4 along with predictions for skewness, kurtosis and directionality, based on a previous literature survey [5]. For a single surface finishing technique, lapping, a decrease in surface roughness results in an increase in skewness and kurtosis. This is perhaps to be expected as a lower $R_a$ is achieved by a longer exposure to the finishing method. However, for the other repeated method (EDM) this phenomenon was not seen, likely due to the highly random nature of the EDM process, which also results in the high level of isotropy seen for these samples. The superfinished sample shows both an unexpectedly high kurtosis and a high level of isotropy. This disagrees with the predictions, however, a comparison between the superfinished and lapped samples could still be made

Table 4. Pre-test surface parameters, both measured and predicted

| Finishing Method | $R_a$ | $S_a$ | $S_q$ | $S_{sk}$ | $S_{ku}$ | Isotropy | Predicted kurtosis/skewness [6] | Predicted directionality [6] |
|---|---|---|---|---|---|---|---|---|
| Lapped | 0.010 | 0.088 | 0.119 | 2.641 | 48.897 | 23.643 | Low | Isotropic |
| Lapped | 0.035 | 0.316 | 0.446 | 1.868 | 9.637 | 24.418 | Low | Isotropic |
| EDM | 0.037 | 0.405 | 0.548 | 1.640 | 6.787 | 59.372 | High | Isotropic |
| Lapped | 0.093 | 0.369 | 0.500 | 1.483 | 7.486 | 67.911 | Low | Isotropic |
| Superfinished | 0.110 | 0.305 | 0.537 | 3.504 | 18.818 | 60.069 | Medium | Anisotropic |
| Lapped | 0.173 | 0.523 | 0.706 | 1.542 | 6.772 | 62.669 | Low | Isotropic |
| Ground | 0.193 | 0.419 | 0.589 | 1.392 | 8.727 | 6.987 | Low | Anisotropic |
| EDM | 0.200 | 0.616 | 0.868 | 1.936 | 9.248 | 63.399 | High | Isotropic |

**Tribological tests**

Tab. 5 shows the results from the tribological tests. To facilitate comparisons an average $R_a$ has been calculated from the $R_a$ values of the flat plates. The guide plate was not included in this calculation because the primary oil degradation occurs at the ball-flat interface

The failure condition was modified to allow inclusion of all of the samples as some of the higher $R_a$ samples did not achieve a friction coefficient greater than 0.27, which is below the standard failure criteria for the SOT (a friction coefficient of greater than or equal to 0.28 for 3 consecutive orbits).

Test M5, in Tab. 5, is significantly out of family and can be assumed to be anomalous and so was excluded from all further analysis.

Direct comparisons can be made between different finishing methods which produce similar $R_a$ values. These are explained in Tab. 5 and allow comparisons between different finishing methods for 3 $R_a$ groups.

Additionally, it is possible to consider the significance of a change in $R_a$ alone. This is achieved by comparing the lapped samples against each other.

**Significance of $R_a$ over other surface parameters**

Figs. 3 and 4 show the trends in lifetime and friction coefficient when the results shown in tab. 5 are correlated with $R_a$. Fig. 3 has a best fit relationship, showing a decrease in $R_a$ providing the expected increase in lifetime. However, there is less of a variation in lifetime for samples with higher $R_a$ values. This effect is more significant in the friction coefficient values shown in Fig 4.

The low $R_a$ EDM samples display a greater friction coefficient than the corresponding lapped samples, however the higher $R_a$ EDM samples experienced a similar friction coefficient to the lapped and ground. This indicates that, at least for low $R_a$ samples, there are other significant surface parameters.

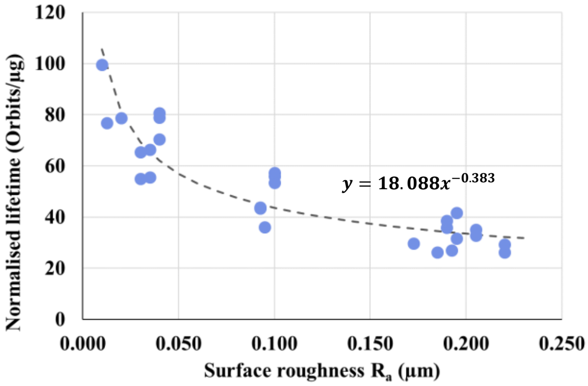


**Figure 3. A power-law trend between $R_a$ and normalised lifetime**

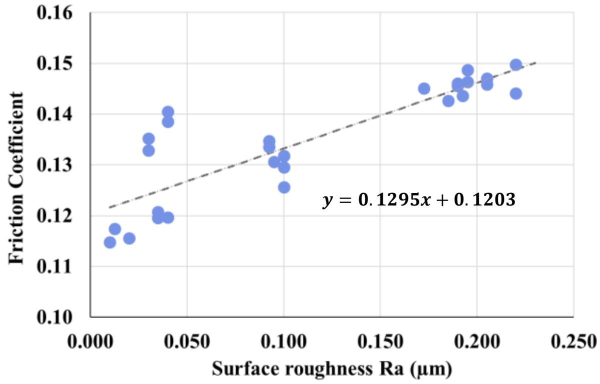


**Figure 4. A linear trend between $R_a$ and mid-test friction coefficient**

In addition to not achieving a friction coefficient greater than 0.27 the highest $R_a$ samples did not show a typical indicator of tribo-chemical degradation of the oil. Oil degradation can be monitored using the chamber pressure as a crude in-situ chemical analysis technique; typically showing an increase in pressure corresponding to the lubricant failure. For the high $R_a$ samples the chamber pressure maintained a constant downward trend, corresponding purely to the continued evacuation. This

Table 5. The results of the tribological tests

| $R_a$ Group | Test ID | Surface finishing method | Average $R_a$ (µm) | Lifetime (orbits/ µg) | Friction (mid-test) |
|---|---|---|---|---|---|
| Very Low | V1 | Lapped | 0.010 | 107 | 0.115 |
| Very Low | V2 | Lapped | 0.013 | 92 | 0.117 |
| Very Low | V3 | Lapped | 0.020 | 98 | 0.116 |
| Low | L1 | EDM | 0.030 | 65 | 0.135 |
| Low | L2 | EDM | 0.030 | 55 | 0.133 |
| Low | L3 | EDM | 0.040 | 79 | 0.140 |
| Low | L4 | EDM | 0.040 | 70 | 0.139 |
| Low | L5 | Lapped | 0.035 | 81 | 0.121 |
| Low | L6 | Lapped | 0.035 | 67 | 0.120 |
| Low | L7 | Lapped | 0.040 | 91 | 0.120 |
| Medium | M1 | Lapped | 0.093 | 73 | 0.134 |
| Medium | M2 | Lapped | 0.093 | 53 | 0.135 |
| Medium | M3 | Lapped | 0.095 | 54 | 0.131 |
| Medium | M4 | Superfinished | 0.100 | 158 | 0.135 |
| Medium | M5 | Superfinished | 0.100 | 56 | 0.132 |
| Medium | M6 | Superfinished | 0.100 | 53 | 0.130 |
| Medium | M7 | Superfinished | 0.100 | 57 | 0.126 |
| High | H1 | EDM | 0.190 | 36 | 0.146 |
| High | H2 | EDM | 0.190 | 39 | 0.146 |
| High | H3 | EDM | 0.220 | 26 | 0.150 |
| High | H4 | EDM | 0.220 | 29 | 0.144 |
| High | H5 | Ground | 0.200 | 32 | 0.149 |
| High | H6 | Ground | 0.200 | 42 | 0.146 |
| High | H7 | Ground | 0.210 | 33 | 0.147 |
| High | H8 | Ground | 0.210 | 35 | 0.146 |
| High | H9 | Lapped | 0.173 | 51 | 0.145 |
| High | H10 | Lapped | 0.185 | 44 | 0.143 |
| High | H11 | Lapped | 0.193 | 53 | 0.144 |

phenomenon was displayed for all the finishing techniques, further indicating that the $R_a$ dominates in these samples.

The significance of $R_a$ in higher $R_a$ samples can be attributed to the same reduction in real contact area, and resulting increase in localised stresses, as previously seen in the $MoS_2$ study [1]. Additionally, higher $R_a$ samples are more susceptible to an uneven distribution of oil across the surface, with possible oil wells and regions of starvation at the asperity tips.

**Specific comparisons between similar $R_a$ samples**

Having examined the significance of $R_a$ without consideration of additional surface parameters, and determining that at least for low values of $R_a$ this is not enough, it is now necessary to compare the surface parameters independent of the $R_a$.

Having confirmed that there is no significant difference in the behaviour of the "high $R_a$" surfaces these comparisons will focus on the "low $R_a$" and "medium $R_a$" surfaces.

**Low $R_a$**

The low $R_a$ comparison (shown in Fig. 5) further shows that the lapped samples have a lower running friction coefficient than the comparison EDM samples. There is no discernible difference in the lifetime of these samples.

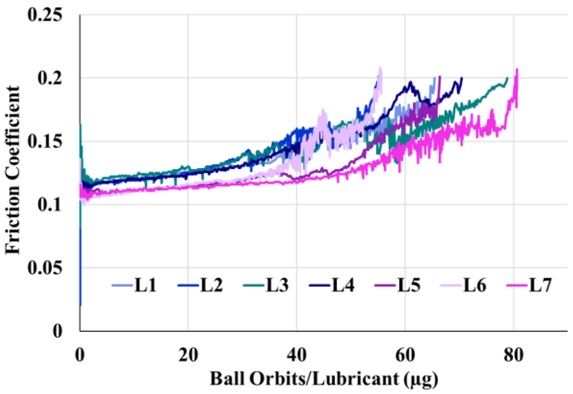


**Figure 5. Low $R_a$ comparison, friction coefficient against orbits/µg**

The EDM samples display an increased running friction coefficient may be due to the increased kurtosis and skewness in these samples. This result is what would be expected from the predicted surface parameter, with EDM having a higher skewness and kurtosis. This corresponds to few, isolated, sharp asperities, which are pronounced in height. These are subjected to localised increased contact stress but are not supporting the entire load. The pre-test profilometry, however, showed the lapped surface having more kurtosis and skewness than the EDM. It can be assumed therefore that the surface parameters are non-uniform.

**Medium $R_a$**

The medium $R_a$ comparison (shown in Fig.6) doesn't show such a prominent difference in running friction coefficient, however, does show a more discernible difference in orbits/µg. The lapped samples in this case have a noticeably shorter life than the superfinished samples. This is unexpected given that the superfinished samples display higher values for skewness and kurtosis and could therefore have been expected to wear more rapidly. This behaviour may be explained by the removal of the amorphous layer (caused by the initial finishing technique, grinding) during the superfinishing process. The underlying material, now exposed, displays different mechanical properties, during testing, to the stressed material, which could be expected to display similar properties as the lapped (which has also been stressed).

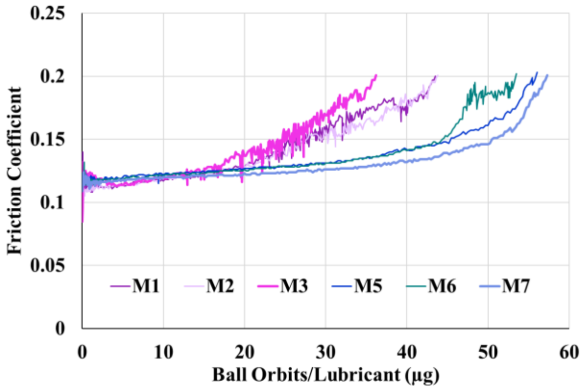


**Figure 6. Medium $R_a$ comparison, friction coefficient against orbits/µg**

**Optical microscope comparison of effect of $R_a$ alone**

The lapped samples were imaged post-test and the effect of $R_a$ on the wear scar was ascertained. There is significant evidence of degraded oil present in the lowest $R_a$ (0.01µm, with obvious dark marks) and the next lowest $R_a$ (0.035µm, with a brown wear scar, and a blackened background). There is some evidence of oil degradation in the higher $R_a$ samples (0.093µm and 0.173µm) however this is less so than in the lower $R_a$ samples, despite having a similar initial oil quantity.

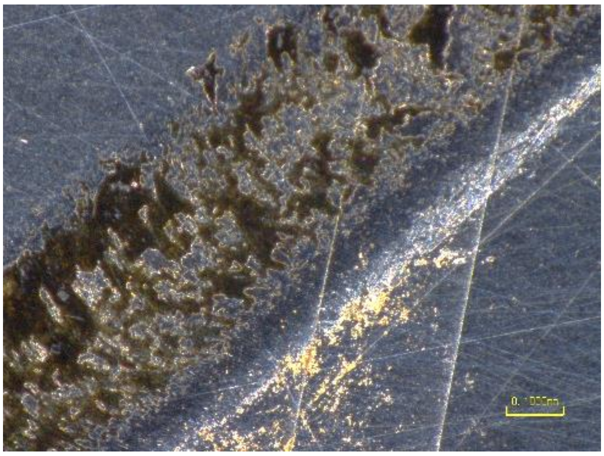

**Figure 7. Very low $R_a$ (0.010µm) wear scar image showing extreme degraded oil**

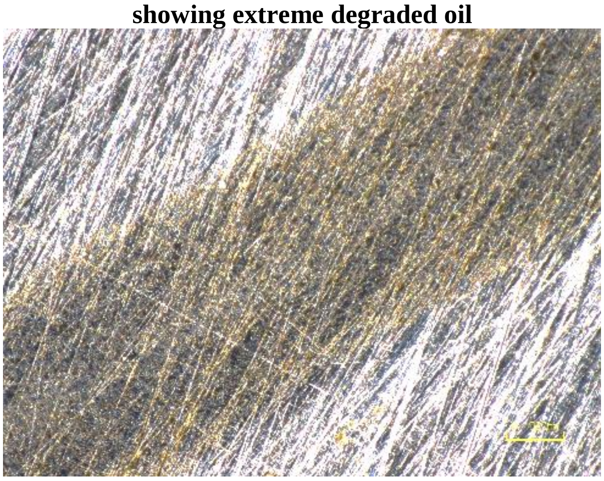

**Figure 8. Low $R_a$ (0.035µm) wear scar image showing oil degradation**

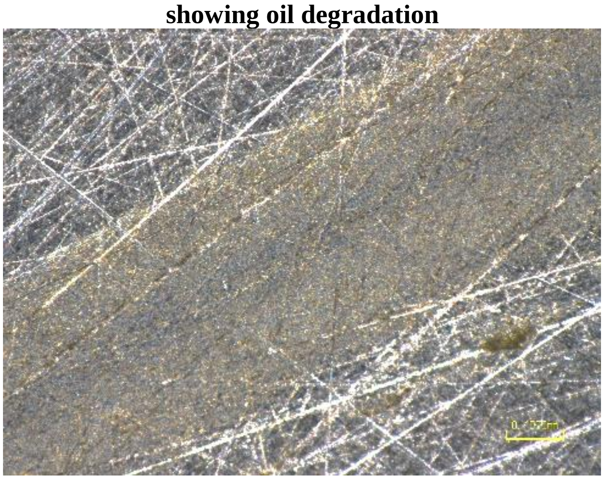

**Figure 9. Medium $R_a$ (0.093µm) wear scar image showing some degraded oil**

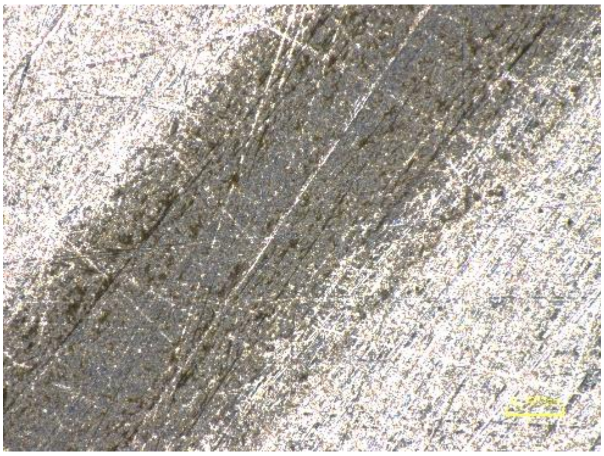

**Figure 10. High $R_a$ (0.173µm) wear scar image showing some degraded oil**

The presence of degraded oil in the higher $R_a$ surfaces indicates that despite the tribological results suggesting that the test did not fail in a traditional manner, the oil was still being sheared as normal. The location of the degraded oil, within remnant machining marks, further supports the idea of oil starvation at the asperity tips and oil wells between them. The presence of localised degraded oil on the medium $R_a$ surface indicates that it is possible for the lubricant to experience a traditional failure even when this starvation/oil well phenomena is present.

**Post-Test Surface Characterisation**

The change in the considered parameters between the pre-test values and those taken after tribometer testing was quantified as a percentage change. The calculated percentage changes are summarised in Tab. 6.

The lapped samples display a trend in the percentage change for isotropy, with increasing initial $R_a$ values showing a corresponding decrease in isotropy after the test, as well as an increase in kurtosis. These can be explained by the different initial wear mechanisms for low $R_a$ and high $R_a$ samples.

The lowest $R_a$ sample shows a large increase in the $S_a$ and $S_q$ parameters. This is unusual however no other finishing techniques which reproduced such a low $R_a$ were included so no comparisons can be made to determine if this was a result specifically of the lapping process or of the $R_a$.

Qualitative pre and post-test profilometry images are included for each comparison (low $R_a$, medium $R_a$ and high $R_a$).

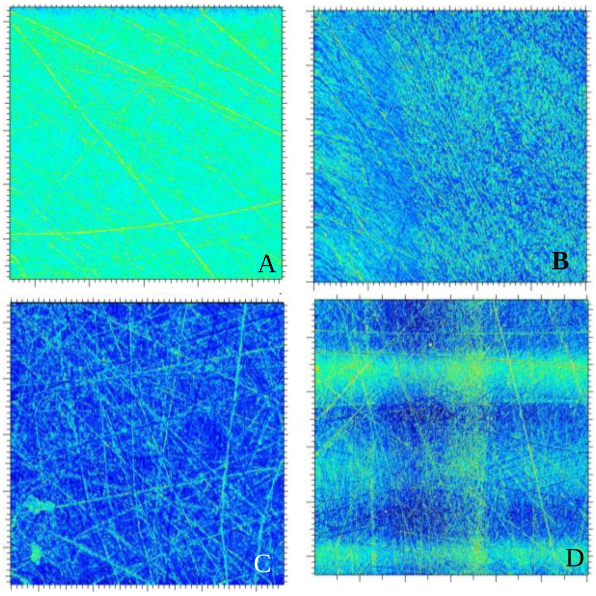


**Figure 11. Low $R_a$ profilometry images. (A) Pre-test lapped sample, $R_a$ = 0.035; (B) Post-test lapped sample; (C) Pre-test EDM sample, $R_a$ = 0.037; (D) Post-test EDM sample**

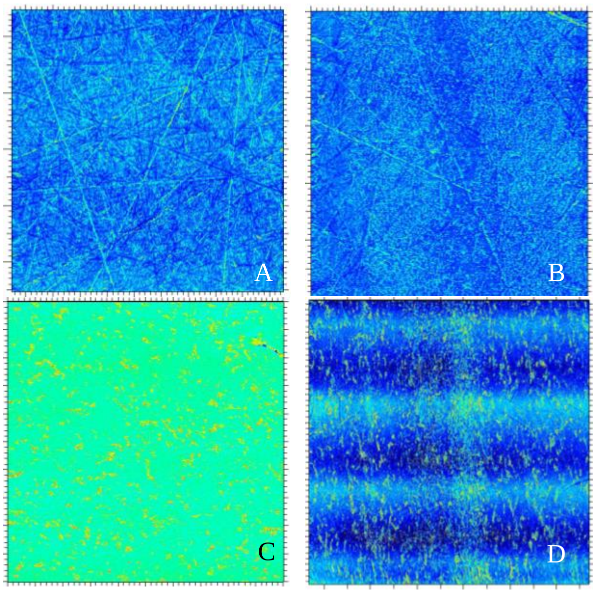


**Figure 12. Medium $R_a$ profilometry images. (A) Pre-test lapped sample, $R_a$ = 0.093; (B) Post-test lapped sample; (C) Pre-test superfinished sample, $R_a$ = 0.10; (D) Post-test superfinished sample**

Fig. 11 shows that for low $R_a$ values the original machining marks are still apparent, regardless of the finishing technique. However, directionality is visually present in the lapped samples. Whilst this is less obvious in the pre-test image (Fig. 11A) the difference in mid-test frictions produced by these two methods suggests that the pre-test directionality is likely to have a severe effect. This is of specific concern to bearing manufacturers (with a typical surface finish requirement of between 0.025µm and 0.125µm). If using $R_a$ values at the lower region of

Table 6. Percentage changes in surface parameters, pre and post-test

| Finishing Method | $R_a$ original | Percentage Change in $S_a$ | Percentage Change in $S_q$ | Percentage Change in $S_{sk}$ | Percentage Change in $S_{ku}$ | Percentage Change in Isotropy |
|---|---|---|---|---|---|---|
| Lapped | 0.010 | 235 | 293 | 5 | -68 | 217 |
| Lapped | 0.035 | 28 | 22 | -15 | -32 | 98 |
| EDM | 0.037 | 4 | -1 | -39 | -37 | -92 |
| Lapped | 0.093 | 28 | 26 | 14 | 9 | 3 |
| Superfinished | 0.110 | 30 | 7 | -40 | -52 | -82 |
| Lapped | 0.173 | 50 | 61 | 28 | 70 | -85 |
| Ground | 0.193 | 10 | 3 | -27 | -42 | 436 |
| EDM | 0.200 | -11 | -19 | -64 | -61 | -51 |

this range, therefore, it becomes necessary to consider the directionality of the surface. If using surfaces with $R_a$ values at the upper end of this range (medium $R_a$) there is the difference in SOT lifetimes, with the superfinished samples achieving a greater (normalised) lifetime to consider. Fig. 12 shows that the superfinished sample has a "speckled" appearance, in both the pre- and post-test image. The absence of the machining marks in this sample, compared to the lapped, is likely the reason behind this increased lifetime. This indicates that the general finishing method is significant across all the $R_a$ values typical of bearings.

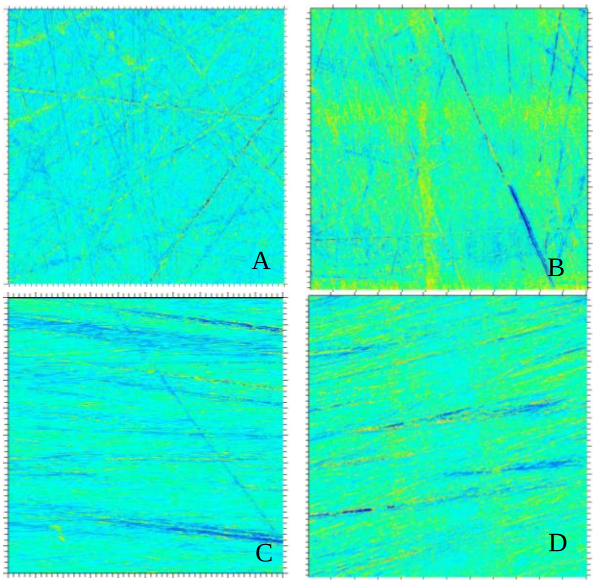


**Figure 13. High $R_a$ profilometry images. (A) Pre-test EDM sample, $R_a$ = 0.205; (B) Post-test EDM sample; (C) Pre-test ground sample, $R_a$ = 0.205; (D) Post-test ground sample**

Fig. 13 shows that at high $R_a$ values the finishing method is unable to remove the underlying surface topography, and thus the initial manufacturing method dominates the performance. In the present study all of the components were manufactured by the same provider, and only the finishing technique was specified, thus all of the underlying machining was performed in the same manner. The primary bulk material removal techniques are hobbing and grinding, both of which are used to achieve the final surfaces for use as gears. These are typically in the range from 0.8µm to 3.5µm for hobbing and 0.1µm to 2.0µm for grinding [5]. EDM is less commonly used to manufacture gears as it is less accurate for complex geometries. This study shows that at these large $R_a$ values the specific finishing technique is less significant and thus supports the use of both grinding and hobbing in gear manufacture, with neither likely to be better nor worse than the other.

## 5. OTHER LUBRICATION TECHNIQUES

Having discovered that the specific surface finishing technique may have an influence on the tribological performance of low $R_a$ surfaces for fluid lubrication with oils, it is logical to consider the significance of surface finishing techniques on grease and solid lubricated contacts.

### Grease

Vacuum greases are more commonly used than oils within spacecraft mechanisms, with their prominence attesting to their usefulness. However, to the authors knowledge, there are no studies specifically investigating the effect of $R_a$ or other surface parameters on its efficacy.

As greases have a greater viscosity than oils it can be assumed that they would be less susceptible to the phenomena of starvation and wells. However, this may mean that they instead display a similar behaviour to low $R_a$ oil lubrication, with tribological performance influenced by additional surface parameters.

### $MoS_2$

A well accepted model exists to compare the effect of underlying surface $R_a$ on the in-vacuo performance of $MoS_2$ [1]. As part of the validation of this model a series of pin-on-disc experiments were performed which found that for increasing $R_a$ values the durability of the $MoS_2$ coating increased, up to an $R_a$ of 0.3µm. For higher $R_a$

values it is often required to apply a thicker initial coating to achieve similar durability. [5] An increase in durability with $R_a$ is the inverse relationship to that for oil lubricants, which have regions of starvation and a less uniform film thickness at higher $R_a$ values. This fundamental difference implies that the observations determined in the present oil fluid lubricant study cannot be directly applied to solid lubricants.

## 6. CONCLUSIONS

- For oil lubricated contacts with high $R_a$ surfaces (>0.2µm, as is typical of gears), the surface finishing technique does not govern the tribological performance
- For oil lubricated contacts with low $R_a$ surfaces (<0.1µm, as is typical of bearings) the surface finishing technique influences the tribological performance.

## 7. FUTURE WORK

An ongoing research activity at the European Space Tribology Laboratory (ESTL) will compare gears produced through both hobbing and grinding. The gears will be manufactured with the same hardness to provide an accurate comparison.

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