INVESTIGATION OF MICRO-MANUFACTURING PROCESS PERFORMANCE VIA INNOVATIVE SURFACE CHARACTERISATION METHODS

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Abstract:

Increasing interest surrounds micro-manufacturing, in part due to the growth of structured surfaces, which require the fabrication of localised micro-scale surface features. Assessment of manufacturing process performance is critical to optimisation of the resulting product and can be addressed by inspection of the resulting geometries. The micrometre scale of features on typical structured surfaces necessitate the use of optical surface topography measuring instruments, common to surface metrology, to measure such surfaces. However, associated conventional surface texture characterisation methods, based on areal texture parameters, often prove inadequate because they fail to capture the relevant geometric properties needed for an effective dimensional verification. The work reported here investigates an alternative route based on determination of dimensional/geometric attributes of the micro-fabricated features. This approach allows for direct assessment of manufacturing process performance by comparison of the geometric attributes with their nominal values. An example application is shown where a micromachining process (laser texturing) is applied to the fabrication of a periodic pattern of cylindrical pockets (dimples) to be used in low-friction bearing surfaces. Fabrication process performance is assessed through the geometric characterisation of the resulting topographies.

Keywords: Structured surfaces, Laser texturing, Surface metrology

1. INTRODUCTION

Structured surfaces are surfaces whose topography consists of generally high aspect-ratio, deterministic features, designed to provide specific functional performance [1]. They are becoming increasingly popular due to their ability to provide improved functional performance for a number of applications, including: friction reduction, wettability and optical effects [2–7]. In order to manufacture such surfaces efficiently, fast, repeatable, low-cost micro-manufacturing techniques are required. Laser surface texturing (LST) is one such technique and has become popular, in particular for the production of low-friction, structured surfaces [8–12].

In order for a structured surface to perform as expected it is necessary for the surface features to closely match the design specifications. Surface inspection and verification are, therefore, necessary and require the capability to measure and analyse the geometries of the micro-fabricated features in comparison to their nominal counterparts. Being able to perform a dimensional and geometric assessment at the feature level can serve also as a tool to understand manufacturing process behaviour and performance, optimise process parameters, and compare manufacturing process variants.

The conventional surface metrology approach for analysing three-dimensional topography data is based on the computation of areal parameters (ISO 25178-2 [13]). However the areal parameters are statistical properties of the entire surface and so not ideally suited to characterising the dimensional and geometric properties of individual surface features.

Recently, an alternative characterisation approach to areal parameters has been proposed, based on identifying and extracting individual surface features, so that they can be subjected to individual, geometric verification [6,12,14,15]. When applied to micro-manufactured features of a structured surface, this approach allows for the implementation of verification procedures akin to those used for quality inspection of standard-sized parts.

This paper explores the application of this alternative approach to the characterisation of individual features on a structured surface, and shows how collected information can be used to gain insight into the performance of the micro-manufacturing process used to fabricate the surface. The test case consists of cylindrical pockets (dimples) in periodic pattern, manufactured by laser texturing over a silicon nitride substrate with the aim of obtaining a low-friction structured surface for bearing applications. Several design variants (different nominal diameters) are considered based on the same reference shape. The depth and projected area of the features is kept constant in all cases. A femtosecond-pulsed laser beam is used to fabricate the dimples, with varying process parameters depending on dimple diameter.

Dimple diameter and out-of-roundness, computed from areal measurement data by means of a dedicated procedure, are chosen as the observation variables. For each design variant, multiple observations are collected by sampling multiple dimples from the each manufactured pattern. For each sample, bias and standard deviation are computed in relation to the nominal diameter, and are used as a means for assessing the performance (accuracy and precision) of the laser texturing process when configured to achieve that specific design variant.

The results for the test case are used as a starting point to discuss how the characterisation procedure aimed at individual surface features can be used to investigate manufacturing process behaviour and performance, highlighting advantages and open issues.

2. MATERIALS AND METHODS

2.1 Specimens and Sampling

Three samples are considered, consisting of silicon nitride disks with a flat top surface and a regular pattern of circular pockets (dimples) designed for friction reduction. Dimples are manufactured via fs-pulsed laser texturing and come in three nominal variants (one per disk) with diameter 50 µm, 150 µm and 300 µm, cylindrical shape, 10 µm depth and 20 % coverage of the surface area. For each disk a sample of 100 dimples, chosen at random from the several thousand on the surface, was collected using an Alicona InfiniteFocus focus variation microscope, with 20× objective lens, 0.40 numerical aperture, field of view 0.715 mm × 0.544 mm. Using this configuration, the result of each measurement process is an image (range image/height map) containing one usable dimple topography. Figure 1 shows an example height-map (150 µm diameter dimple). The magnification was chosen as the best option for ensuring that all three dimple diameters would fit into a single image.

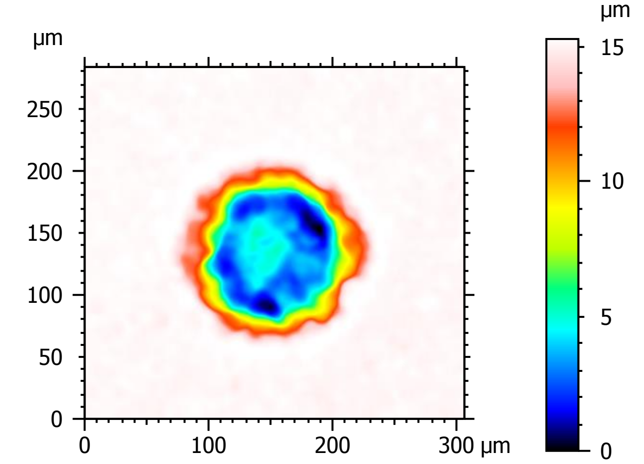

Figure 1: Height-map of a dimple with nominal diameter 150 µm. Image was cropped to exclude portions of neighbouring dimples appearing at the image boundaries.

2.2 Computation of Dimple Diameter and Roundness Error

A dedicated procedure aimed at computing dimple diameter and roundness error from each dimple topography was developed. The procedure follows the recent approach to surface topography characterisation based on targeting dimensional and geometric properties of individual surface features, as opposed to computing areal texture parameters. The general approach is illustrated in detail elsewhere [13,14]. The dedicated procedure consists of multiple steps, as illustrated in the following, with the help of figure 2, and has been implemented in Matlab. Additional comments on the procedure are discussed in section 4.

1. Pre-processing: this step consists of smooth filtering and levelling the raw height map. A convolution filter with a Gaussian kernel (1.6 µm standard deviation) is used for smoothing; levelling is carried out by subtraction of a least-squares mean reference plane fitted to the surface points surrounding the dimples. This type of selective levelling is used so that the heights of different dimples are all referred to the same planar reference approximating the disk support surface. Further details can be found in previous work [15].
2. Segmentation: the image is partitioned into different regions (segments), each characterised by uniform topographic properties. The overall goal is to obtain a partitioning that can be used as a good starting point for separating the dimple from its surroundings. For this application, as the dimple surface is more irregular than the support surface (due to the characteristic footprint of laser texturing), segmentation is based on local gradient information. The local gradient is computed as the magnitude of the Sobel operator [16] as shown in figure 2a. A binary classification map is obtained by setting a threshold at 0.5 (figure 2b). The importance of setting the correct threshold value is discussed later in section 4.
3. Post-processing and identification of the surface feature: the classification map produced by segmentation is further processed in order to better capture the separation between the dimple and its surroundings, as shown in figure 2c. In particular, smaller (< 5000 pixels) misclassified regions enclosed within the two main partitions (due to gradient thresholding reacting to local singularities in the topography) are removed via filling. Feature identification (*i.e.* recognising one of the two partitions as an instance of the feature of interest – dimple) is done algorithmically by selecting the region that is topologically disconnected from the image boundaries.
4. Identification of reference geometry for the feature: the term reference geometry refers either to a portion of the available feature topography, or to analytical geometry fitted to it. Reference geometry is needed to compute the target feature attributes: for example, the dimple boundary in the image plane, and the analytic circle fitted to it are the reference geometries needed to compute dimple diameter and roundness error. The dimple boundary is extracted as the set of pixels at the boundary of the dimple region in the segmentation map; the analytic circle is computed via least-squares circle fitting to the dimple boundary (LSCI circle - ISO 12181-2 [17]).
5. Computation of the target feature attributes: dimple diameter is retrieved as the diameter of the LSCI; roundness error is calculated as peak to valley out-of-roundness on the LSCI, *i.e.* maximum departure of the profile from the least squares reference circle (the highest peak to the lowest valley). Figure 2d shows the fitted circle plotted back onto the original topography.

2.3 Statistical Analysis

For this work it is assumed the diameters are independent and normally distributed such that the sample mean and variance are good estimates of the population and confidence intervals for mean and variance are given by the normal and Chi squared distributions respectively. Initial investigations indicate this is a reasonable approximation for the current samples.

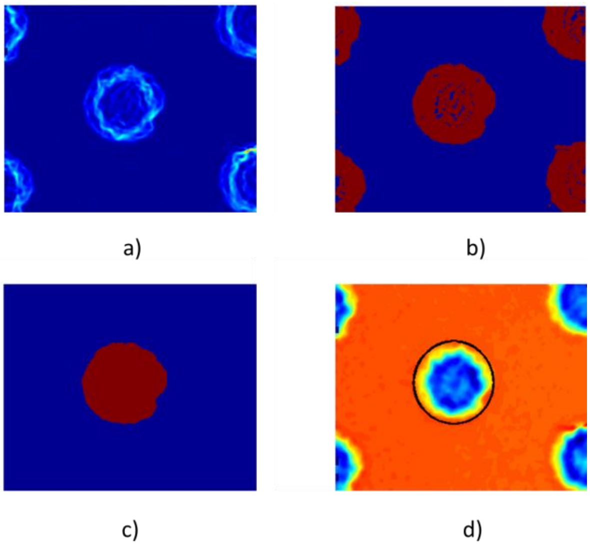

Figure 2: The dedicated procedure for computing dimple diameter and roundness error: a) gradient map calculated from the height data; b) segmentation map; c) post-processed map and feature identification; d) least squares reference circle (black) fitted onto the dimple boundary and plotted back onto the height-map.

The diameter bias is calculated from the difference between the nominal and measured diameters, and it is used as an indicator of manufacturing performance to assess the accuracy of the size of the dimples. Similarly the standard deviation of the bias provides an indicator of the dimensional precision with which the dimples are manufactured.

The other indicator considered is the out-of-roundness (OoR), which provides indication of the shape of the dimples. Similar to the diameter bias, the mean out-of-roundness indicates the accuracy of the shape and the standard deviation indicates the precision.

It is suggested that the magnitude of both the bias and out-of-roundness are dependent on the nominal diameter. Therefore, normalised versions of these parameters were calculated by dividing the results by the nominal diameter. This normalisation facilitates comparison between the different sized dimples.

3. RESULTS

The selected dimples where measured and analysed as described in section 2. The associated statistics are summarised in table 1. Absolute values are shown in figure 3; values normalised by associated nominal diameter are shown in figure 4.

The 150 µm samples have the smallest absolute bias and, unlike the other two sample diameters, the bias is negative. That is, the average diameter is larger than the nominal diameter. There are several possible explanations for this result. Better optimisation of threshold parameter and other processing steps used for the characterisation may be needed for this diameter. However, if this was the complete explanation, a linear pattern of the diameters would be

Table 1: Mean and standard deviation (std) of measured diameter, bias and out of roundness for each set of samples.

	50 µm		150 µm		300 µm	
	mean	std	mean	std	mean	std
Diameter (µm)	42.68	3.03	152.23	1.94	294.56	5.22
Bias (µm)	7.32	3.03	-2.23	1.94	5.44	5.22
Normalised Bias	0.15	0.061	-0.015	0.013	0.018	0.017
OOR (µm)	8.30	2.22	16.68	3.78	23.08	6.51
Normalised OOR	0.17	0.044	0.11	0.025	0.077	0.022

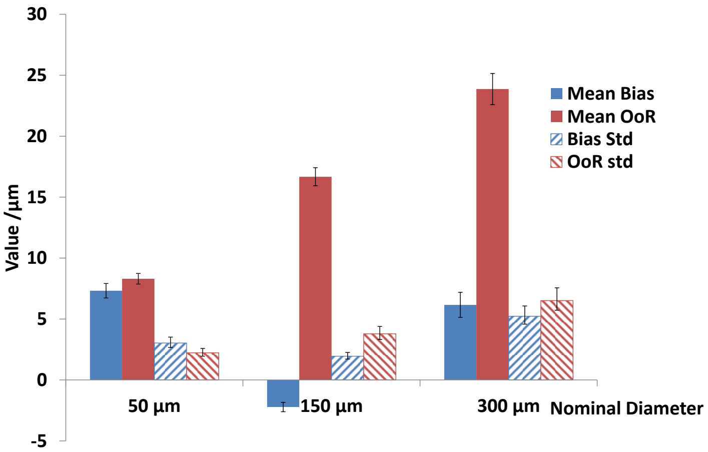

Figure 3: Means and standard deviation (std.) values for diameter bias and out-of-roundness (OoR) for each set of samples. Error bars indicate 95 % confidence intervals.

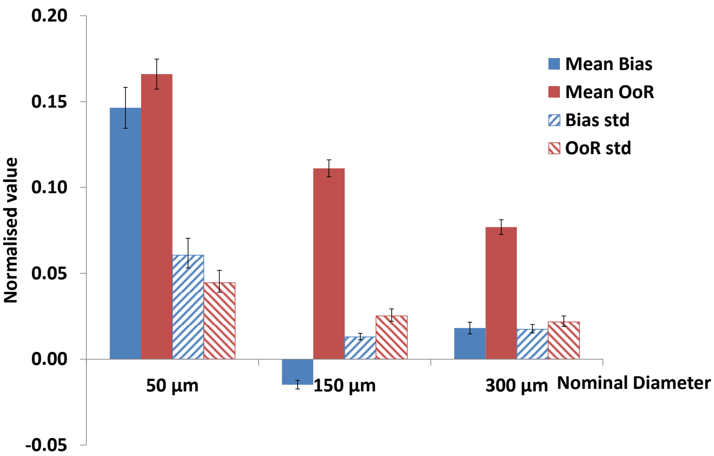

Figure 4: Means and standard deviation (std.) values for diameter bias and out-of-roundness (OoR) or each set of samples, after normalisation by the nominal diameter of the associated sample. Error bars indicate 95 % confidence intervals.

expected. Since this is not the case, it is suggested that there is some significant change in the feature topography as the diameter changes. This change in topography is probably due to the manufacturing process, and in particular the degree to which it is optimised to produce a specific dimple diameter.

Figure 3 indicates that the mean and standard deviation of the out-of-roundness increase with dimple radius. This pattern would appear to suggest that larger dimples have rougher edges that are less circular than for smaller dimples.

However, when the data is normalised by the nominal radius, as in figure 4, the opposite pattern is observed. While smaller dimples have smaller deviations from the nominal in absolute terms, the deviations are larger relative to the dimple size. This effect highlights one of the critical issues with micro-manufacturing processes: as feature size decreases, deviations from the nominal geometry become more significant in relative terms.

4. DISCUSSION

From the results presented in section 4 it can be concluded that the 50 µm diameter dimples are more strongly affected by the manufacturing process than the larger dimples; the normalised bias and out-of-roundness are both largest for the 50 µm dimple. This result is to be expected. As the feature size decreases, local effects, such as material grain size and variations in the laser focus, will have a more significant effect.

The physical meaning of these results must also be considered. The physical boundary of a feature is difficult to define and in this case is only defined by the characterisation method. This would motivate exploration of the effect of changing the characterisation method. It is reasonable to assume that a different characterisation method will also change the measured diameter and out-of-roundness. The characterisation method detects the feature boundary; different methods will establish different boundaries and different values for parameters determined from the boundary. It is therefore prudent to question what information the bias gives. In many ways the bias is just an indication of how well the algorithm is tuned for a particular measurement. However, the fact that the bias does not show a linear relationship suggests that the topography does have some influence.

Another factor to consider is the sample selection process. In this paper it has been assumed that, because a random sample of dimples was selected, the measurements of different features were uncorrelated. However, this assumption may be invalid. In particular it is suspected that there is significant spatial correlation between features on the surface. The effect of such correlation is that features that are close together on the surface are likely to be more similar than those far apart. Therefore, the parameters calculated using this data may be skewed, particularly for the standard deviations. More research is needed to assess, quantify and account for this correlation and the effect it has on statistics of the measured parameters. In this particular test case, samples were randomly selected from across the entire disk, in order to mitigate the correlation effect.

5. CONCLUSIONS

Three structured surfaces, manufactured by different process variants to have different nominal diameters, were measured and characterised to determine their feature diameter and out-of-roundness. Bias from the nominal diameter was lowest for the 150 µm dimples, suggesting that the manufacturing process is best optimised to produce a 150 µm diameter. When normalised by the nominal diameter, the mean and standard deviation of the bias of the 50 µm dimples was significantly higher for the 150 µm and 300 µm dimples, suggesting a poor optimisation of manufacturing process for diameter, possibly because of the small size.

For out-of-roundness, when considering the absolute value the out-of-roundness appears to increase with diameter. Following normalisation with the nominal diameter, however, the opposite relationship was observed. This suggests that smaller features have more significant out-of-roundness, which implies a lower limit on the feature size that could be usefully manufactured using this process.

The significance of the choice of characterisation method, particularly the thresholding parameter, was also discussed. Change of the characterisation method may produce a significant change in measured dimple geometry. However, the observation variation in the presented results cannot be attributed solely to the characterisation algorithm choice. It is suggested that significant additional variations exist between the actual topography generated by the different manufacturing process variants, manifesting as variation in accuracy and precision across the sample sets.

ACKNOWLEDGEMENTS

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