The use of areal surface topography characterisation in relation to fatigue performance

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Abstract. Although the effect of surface topography on fatigue life is widely accepted, the underlying role of surface roughness from first principles is still poorly understood. Currently approaches which consider the influence of surface roughness on fatigue life prediction can be broadly classified into surface corrector factors (C_s) and stress concentration factors (K_t). Those approaches describe the surface according to the manufacturing process (machined, grounded…), or using 2D height descriptor parameters (R_a, R_z...). However, these approaches are not able to correctly describe the effect of roughness on the fatigue performance where it is anticipated a richer set of surface descriptors would show correlation. The present work aims to highlight the inherent limitations of the most commonly employed 2D surface measurement and characterization techniques, and provides an insight into the application of 3D areal surface characterization processes including the use of the latest areal surface topography parameters quantifying amplitude, spatial, and hybrid topographical information which is considered to be important for fatigue performance correlation.

1 Introduction

The influence of surface topography on fatigue strength is widely accepted. The micro-geometrical irregularities that constitute surface roughness can be treated as microscopic notches, which promotes crack initiation through local stress concentrations, reducing life-to-first-crack and hence total fatigue life [1-2]. Although other surface quality parameters can also affect fatigue behaviour (*i.e.* microstructure and residual stresses) [3-4], the impact of surface topography becomes more significant when crack initiation life is notable (*i.e.* in high cycle fatigue, HCF) [5-6].

One of the earliest published work on the effect of workpiece surface topography on fatigue life was conducted by Thomas in 1923 [7], which identified the detrimental effects of microgeometrical irregularities on fatigue behaviour. Since then, several studies on the role of roughness on fatigue life have been published [8-9].

Technical literature provides an empirical correction factor, generally known as surface factor C_s, [10] that can be used to adjust the endurance limit if surface roughness is different from standard specimen conditions. This surface finish corrector factor categorizes finish in qualitative terms according to the manufacturing process (machined, forged...), or presents the surface finish correction factor in a more quantitative way by using quantitative measure of surface roughness according to the average roughness amplitude (R_a). The asperities that constitute surface roughness can also be treated as microscopic notches by introducing a stress concentration factor K_t. This factor can be calculated either from averaged geometrical parameters of the surface [11], and or by finite element analysis (FEA) [12].

The average roughness amplitude, R_a, remains the most widely used parameter to describe fatigue specimen roughness. However, as the critical functional role played by the surface roughness on fatigue performance gains recognition, there is an increasing need for more function related surface characterization procedures in order to describe and identify the features affecting fatigue performance.

The present work aims at highlighting the inherent limitations of the most commonly employed 2D surface measurement and characterization techniques, and provide an insight into the 3D/areal characterization process and latest areal surface topography parameters important in fatigue performance correlation.

2 Critical Analysis of R_a

Current approach to characterize surface roughness of fatigue specimens typically rely on a single amplitude parameter, R_a, which describes the arithmetic average value of the deviation of the trace above and below the centre line (see equation 1) [13]. Higher values of R_a are usually related to lower fatigue strength.

$$R_a = \frac{1}{N}\sum_{i=1}^{N}\left|y_i\right| \qquad (1)$$

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While R_a remains useful for quality control once a well defined manufacturing process is shown to be sufficiently stable, it typically proves too general to describe the surface's functional nature. Topography characteristics that have high impact on fatigue strength, such as tip radius of micro-notches and spacing between notches are not taken into account, since R_a only quantifies vertical values of the surface.

In order to show the influence of the tip radius and micro-notch spacing on fatigue, 2 simulated sine wave surfaces were generated with the same R_a value (see Figure 1). By changing the frequency of the sine, different tip radii and notch spacings were obtained. It is noteworthy that these profiles also present the same R_t and R_z values, defined as the total height of the profile evaluation length, and the average maximum height of the profile calculated at each sampling length, respectively [13]. Those parameters describes the extreme height characteristics of the profile and has been suggested as good fatigue performance predictors due to their capability to reflect the 'worst' defects present in the workpiece [14].

Two dimensional (2D) uniaxially loaded FEA has been performed (Figure 2) to obtain the K_t generated by these profiles, computed as:

$$K_t = \sigma_{11}/\sigma_\infty \, , \qquad (2)$$

where, σ_{11} is the normal stress and σ_∞ is the applied remote stress. Since $\sigma_\infty = 1$ MPa, K_t is equal to σ_{11}.

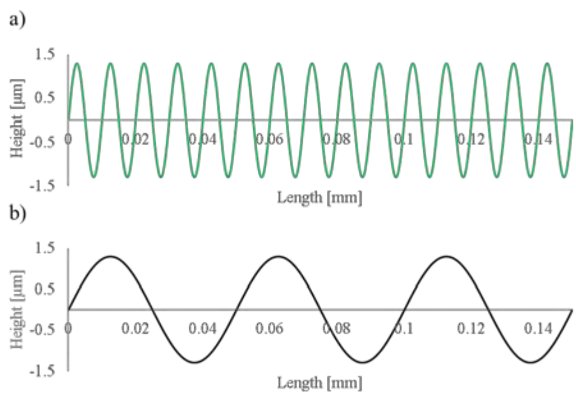

Fig. 1. Simulated profiles, R_a = 0.8 μm in all cases. a): wavelength of 50 μm. b) wavelength of 10 μm.

Studies of crack nucleation under uniaxial and multiaxial fatigue loading reveal that fatigue damage starts in an individual crystal, usually at the surface [15]. From this standpoint, higher values of K_t will lead to lower cycles to crack initiation and therefore to shorter lives.

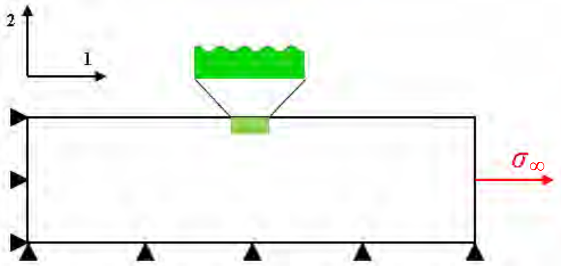

Fig. 2. Applied boundary condition and forces of the numerical models.

Figure 3 illustrates the results of the 2 monotonic tensile simulations. As expected, the maximum K_t is associated with the deepest topographic location in all simulations. Additionally, the minimum K_t are linked with the highest points due to the stress relaxation produced by the local loss of stiffness.

It can be observed that the first profile, with the smallest tip radius and shortest notch spacing, presents the maximum stress concentration. From a fracture mechanics point of view, small tip radii are linked with shorter fatigue lives [16]. Regarding the notch spacing effect on fatigue life, literature shows that shorter notch spacing suggests longer lives due to the so called 'notch interference effect'[6]. It should be highlighted that such statements correspond to the spacing effect for equal valley tip radius, which is not the case of the present profiles. However, the notch interference effect is visible in the present profiles. It can be observed that the stress relaxation produced at the highest topographic location are more pronounced in the shortest spacing profile. Therefore, lower K_t could be expected on shorter spacing profiles for the same theoretical tip radius, which is consistent with the literature.

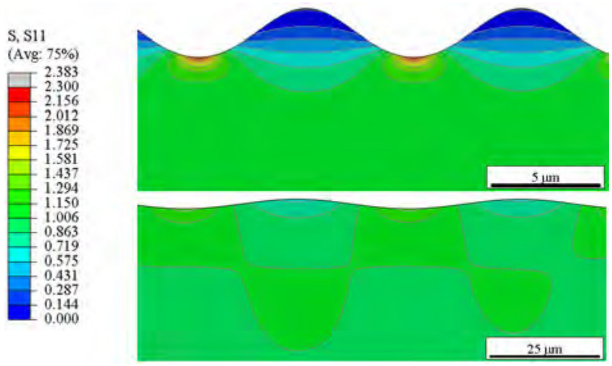

Fig. 3. FEA results of the simulated profiles. Upper figure: wavelength 10 μm, K_t=2.3; Lower figure: wavelength 50 μm, K_t=1.4.

As mentioned previously, higher K_t values are associated with shorter crack nucleation cycles. However, another important role on fatigue is the stress gradient effect. High stress gradient indicates that the stress decays rapidly near the hot spot. Thus, for the same K_t value, a crack of certain length will grow faster if a low stress gradient exists, thus leading to shorter fatigue life.

Figure 4 shows the K_t evolution for each profile below the surface. On the one hand, it is observed that the highest K_t profile shares also the highest stress gradient. On the other hand, the lowest K_t profile also has the lowest stress gradient. Therefore, from a certain depth onwards a crack will growth faster in the simulation with the lowest K_t [17].

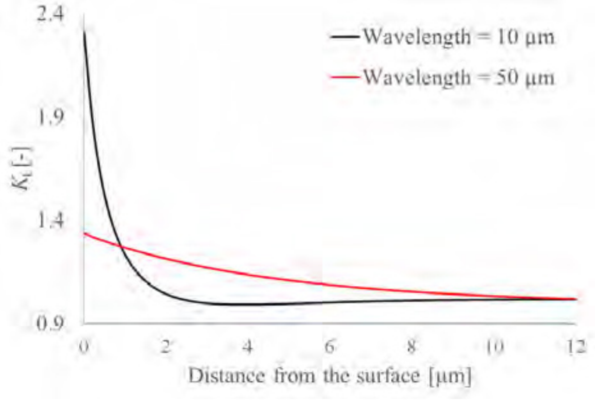

Fig. 4. Stress concentration factor (K_t) at different depths below the surface for the 2 simulated surfaces.

This analysis highlights the inherent limitations of the R_a parameter. Different profiles with the same R_a could show different characteristics in terms of stresses leading to different fatigue lives. Therefore, the average roughness amplitude parameter may not be best suited to describe the role of surface roughness on fatigue strength.

3 2D (profile) Vs 3D (areal) Characterization

2D profile measurement and its analysis is still playing an important role in the assessment of surface topography. This traditional technique is based on a contact stylus measurement system, where the stylus is moved across the surface to be measured for a pre-determined trace length while recording the vertical deviations of the stylus and thus the surface. The positive features of the technique that makes it currently preferred in the industry are mainly based on the short time needed to measure the profile, the lower cost of the instrument, and the fact that the process is well-established [18]. The surface topography is however three dimensional in nature, and there are inherent limitations to the use of these 2D techniques.

Profile measurement and its characterisation makes it difficult to determine the exact nature of the areal surface topography. Figure 5 presents a profile (2D) and areal (3D) representation of the same component covering the same measurement area. While the valleys present on the surface are clearly identified in the areal representation, it is impossible to identify whether they arise from pits or valleys in the 2D profile.

Areal measurement is able to provide a more complete information regarding the surface topography, not only in the qualitative identification of the surface features (pits, troughs, lay…), but the sizes, shapes and volumes can also be quantitatively calculated. Since 2D profiles coincides with an intersection of a vertical plane with a measured surface, it may not cross surface summits or valleys contained within a real surface.

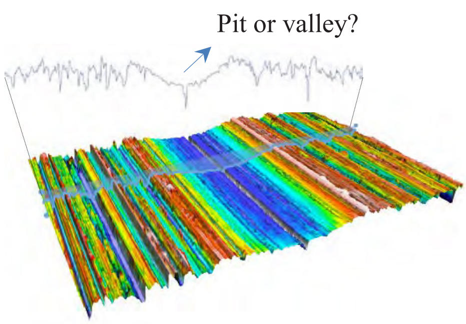

Fig. 5. A profile taken from an areal measurement showing the possible ambiguity of 2D measurement and characterization

It should be also considered that areal measurement presents more statistical significance than the equivalent profile measurement. The larger volume of data obtained increases the independence of the data, reducing the variance of parameters and resulting in a closer representation of the 'real surface' [19].

Finally, it should be noted that the stylus geometry influences the amount of information that can be extracted from a given surface. The stylus tip, which is typically 4 micron diameter 60o subtended cone, produces smoothing of the true profile, due to a mechanical filtering effect (Figure 6).

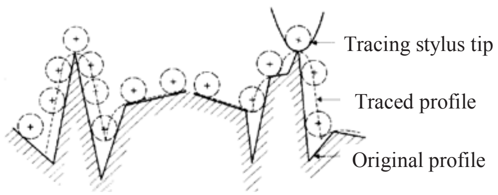

Fig. 6. Mechanical smoothing due to stylus tip diameter [20].

Areal (3D) characterization should therefore provide a more precise representation of the surface topography, and may allow a more precise correlation with fatigue behaviour.

4 3D Topographical parameters for fatigue

As stated by X. Jiang *et al.* the surface metrology discipline is undergoing a huge paradigm shift over the last decades, from profile to areal (3D) characterization [21]. The recently published ISO 25178:2 [22] standard encompass over 30 topographical parameters for surface topography characterization. Regarding the naming rules of the areal parameters, the upper letter '*S*' (for 'surface') is used in 3D instead of the '*R*' (for 'roughness') in 2D. It should also be noted that unlike 2D parameters, which are evaluated along several sampling length, the 3D parameters are determined within one sampling area and there is no distinction in nomenclature as to whether they derive from primary, roughness or waviness information.

Historically adopted taxonomies such as roughness and waviness has been replaced by the scale-limited surface concept, surface from which the topographical parameters are computed. The scale-limited surface represents the resulting surface after the post-processing, which is based on: (i) the removal of the irrelevant form and translation errors, and (ii) filtering (if applicable) to remove non desired frequency components from the study. Unlike 2D characterization, where filtering is systematically applied, the idea of functional filtering is gaining recognition. As stated by Stout et al. [23], filtering should be applied only when the bandwidth of the frequency contents affecting the functional properties is understood. Therefore, it is suggested that surfaces should not be further filtered after eliminating the form components for fatigue performance analysis.

Areal parameters are classified into field and feature parameters. The field parameters are based on statistics of the whole surface whereas the feature parameters are defined over data from previously identified segments of the surface texture. Several areal parameters have been identified as potential indicators of fatigue performance. A summary and description of the most significant areal parameters is presented in this section, where:

- The discrete approximations of the formulas are given since surfaces are always sampled and digitised (for continuous descriptions of the formulas the reader is referred to [24]).
- Figure 7 shows the coordinate system used to define 3D topographic parameters, where η is the mean value surface (the reference datum).

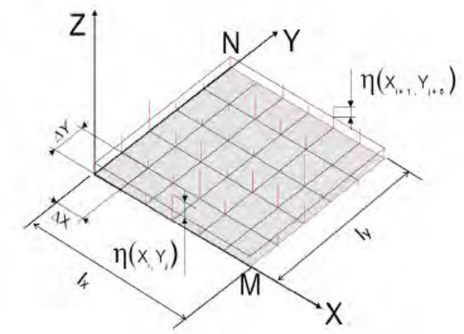

Fig. 7. Coordinate system used to define 3D topographic parameters.

4.1 Height parameters

Fatigue life is strongly dependant on surface roughness when the average asperity heights exceed the intrinsic defects in material [16]. The height descriptor parameters are therefore necessary for surface characterization of fatigue specimens. Among height descriptors, the average roughness (S_a), analogous to the 2D R_a is defined as:

$$S_a = \frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M}\left|\eta\left(x_i, y_j\right)\right|, \tag{3}$$

where M and N are the number of samples in each axis. As mentioned in the section 2, the characterization should include however, other parameters in order to characterize all attributes that affects fatigue life. As demonstrated by Andrews *et al.*, the average fatigue life decreases with increasing the standard deviation in asperity heights [16]. Therefore, the root mean square height parameter, which corresponds to the standard deviation of heights, should also be included in the analysis:

$$S_q = \sqrt{\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^2\left(x_i, y_j\right)}. \tag{4}$$

Among parameters describing the extreme characteristics of surface height, the S_v parameter, which describes the maximum valley depth has been highlighted. As expected, high values of S_v has been correlated to lower fatigue strength [24].

Due to the predominant functional role of the valleys over the peaks on fatigue performance, the Skewness parameter has the potential to deliver functionally useful results regarding surface valleys. The skewness quantifies the symmetry of the height distribution and mathematically is evaluated as follows:

$$S_{sk} = \frac{1}{MNS_q^3}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^3\left(x_i, y_j\right). \tag{5}$$

A negative S_{sk} indicates a predominace of valleys, whereas a positive S_{sk} indicates a predominance of peaks.

Additionally, the Kurtosis of the surface describes the spread of the height distribution, and is described as:

$$S_{ku} = \frac{1}{MNS_q^4}\sum_{j=1}^{N}\sum_{i=1}^{M}\eta^4\left(x_i, y_j\right). \tag{6}$$

A Kurtosis value higher than 3 (S_{ku}>3) indicates a narrowing of the height distribution function and presents physically as a more 'sharply peaked' surface. A purely Gaussian surface would have an S_{sk} value of 0 and an S_{ku} value of 3

Consequently, a negative S_{sk} and high value of S_{ku} could indicate a reduced fatigue life. However, it should be noted that the S_{ku} parameter in particular is very sensitive to surface outliers and as a result can present a high dispersion.

4.2. Spatial parameters

Spatial parameters are determined and quantified by tools based upon the Fourier transform and autocorrelation, detailed descriptions can be found in [19].

As demonstrated in section 2, the spatial properties of the texture has a strong impact on the stress concentration, and by extension, in fatigue life. Accordingly, the fastest decay autocorrelation length parameter, S_{al}, has been suggested as good fatigue performance indicator [24]. This parameter is described as the horizontal distance of the autocorrelation function having the fastest decay to 0.2, and is a quantitative measure as to the distance along the surface by which one would find a texture that is statistically different from the original location. Therefore, a large value of S_{al} denotes that the surface is dominated by long wavelength components, *i.e.* that the texture presents big spacing and vice versa. Suraratchai *et al.* [12] analysed the effect of the texture orientation relative to the axial loading direction on the fatigue life, demonstrating that when the groove direction is parallel to the loading axis, the stress concentration factor generated is very low. The characterization of the directionality of surface texture is therefore highly interesting. The texture aspect ratio parameter, S_{tr}, allows to identify texture pattern, *i.e.* to evaluate if the texture is directional or not. The value of this unit-less parameter ranges from 0 to 1. If S_{tr} value is near 1 this indicates that the surface is isotropic (*i.e.* it has the same characteristics in all directions, *e.g.* sand blasted surface), and in case of being near 0 corresponds to anisotropic surfaces (*i.e.* has an oriented and/or periodic structure, *e.g.* machined surface). For cases where the directionality is identified (S_{tr}~0) the texture direction parameter, S_{td}, calculates the texture direction of the surface expressed in degrees, anticlockwise.

4.3. Functional parameters

Functional parameters are calculated from the Abbott-Firestone curve (also called the areal material ratio curve) obtained by the integration of the height distribution of the whole surface. It represents the percentage of material traversed (in relation to the area covered) for a given depth, and allows analysing the surface properties at different regions (peak, core, valley). The ISO 25178-2 standard defines two arbitrary thresholds (10% and 80%) to define these regions, and the functional parameters are calculated following this definition. The void volume parameter, V_{vv}, has been identified as good fatigue performance indicator. This parameter is defined as the void volume in the valley zone from 80% to 100% surface material ratio, as shown in Figure 8).

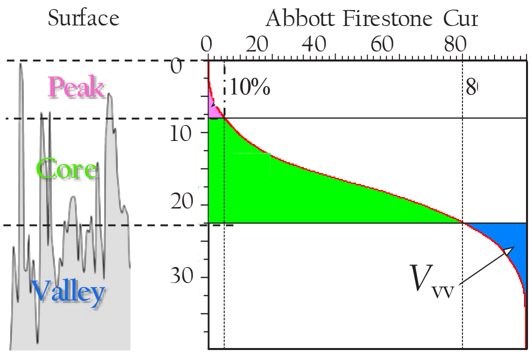

Fig. 8. Abbot Firestone Curve (in red). Peak (pink), core (green) and valley (blue) regions identified, according to the default threshold defined in ISO 25178-2 values (10%, 80%).

Smaller void volume values could correspond to larger tip radius at the root of valleys, which turns to better fatigue performance [23].

5. Conclusions

In this work, the inherent limitations of the most commonly employed 2D surface measurement and characterization techniques has been presented. It has been shown that defining topography based on the average roughness (R_a) is inadequate for correlating with fatigue performance.

Areal (3D) topographic characterization allows a better representation of the surface. An insight into the 3D areal characterization process and latest areal surface topography parameters critical for fatigue performance prediction has been given. Based on the current knowledge, the following areal parameters are suggested to use for topographic characterization for correlation with fatigue performance: S_a, S_q, $S_{al,}$ $S_{sk,}$ and V_{vv}.

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