RELATIONSHIP BETWEEN VALUES OF PROFILE AND AREAL SURFACE TEXTURE PARAMETERS

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This paper presents a regression analysis of the relationship between values of profile and areal surface texture parameters extracted from the same surfaces. The problem of tolerancing for areal surface texture evaluation is briefly introduced. Basic concepts of and differences between areal and profile evaluation are discussed. Measurements of 21 samples of diverse origin are used as data for linear regression of dependencies of areal surface texture parameters *Sa*, *Sq* and *Sz* on their roughness profile equivalents *Ra*, *Rq* and *Rz*. Recommendations for calculation of areal surface texture parameter's tolerance values are discussed based on the results of the analysis. The resulting regression equations provide a fast method for selection of areal surface texture tolerance values based on previous experience with profile parameters.

KEYWORDS

surface texture, surface metrology, areal surface texture parameters, tolerances, regression

1 INTRODUCTION

Surface texture has a significant impact on both manufacturing processes and intended function of a wide variety of machine parts. During the 20th century, its evaluation progressed from simple visual and tactile inspection by a skilled worker to increasingly sophisticated methods [Bumbalek 1989], [Whitehouse 1994].

The current dominant method of evaluation is the profile method, developed in the 1930's. According to this method, surfaces are evaluated based on statistical processing of profiles typically obtained by a contact profiler. Although it was without doubt a great improvement over previously used subjective methods of evaluation, it was soon recognized that simple evaluation of a profile section of a surface was often not sufficient to account for its function [Whitehouse 1997].

This shortcoming was addressed in the recent years by the development of areal surface texture evaluation and 3D surface texture measurement. This was developed to provide a more complex view of a surface and its characteristics by extending the evaluated dataset in the lateral direction.

Despite its improvements over the established profile measurement, 3D surface texture measurement has not yet been widely deployed in the manufacturing industry [Jankovych 2014].

One of potential barriers to industrial 3D surface texture evaluation is the lack of experience with areal surface texture specification. Considerable work is being done in this area by author such as [Yaolong 2015] who groups the available areal parameters based on their correlation in order to aid designers with selection of appropriate specification. Other authors such as [Pawlus 2015] attempt to identify parameters, which are robust in regard to surface variations, thus providing reliable specification.

Another barrier to the adoption of areal surface texture evaluation is the lack of tables of recommended areal surface texture parameter values. Such tables for the most common profile parameters are usually used by designers to select appropriate specification tolerance values for a desired function of a surface as well as manufacturing parameters.

So far, manufacturing tables for areal parameters have been constructed on a small scale based on experimental production, such as in [Mouralova 2016]**.** Such studies require tremendous effort, especially should they be attempted using as many diverse manufacturing technologies as possible.

If a simple mathematical relationship existed between values of profile and areal parameters, regardless of particular surface topography or manufacturing method, existing tables for profile parameters could easily be adapted for areal parameters. That might significantly ease the proliferation of 3D surface texture evaluation in manufacturing quality control.

This paper aims to evaluate the relationships between values of three common roughness profile parameters and their areal equivalents on a wide range of samples manufactured by diverse methods.

2 PROFILE AND AREAL METHODS OF SURFACE TEXTURE EVALUATION

Both profile and areal evaluation of surfaces are based on identification of features on or statistical processing of data extracted from the measured surface, be it a profile or a scale-limited surface.

Surface profiles are divided by the center line into peaks, which are parts of the profile above the center line, and valleys below the center line. Adjacent valleys and peaks form so-called profile elements (Fig. 1) [ISO 4287:1997].

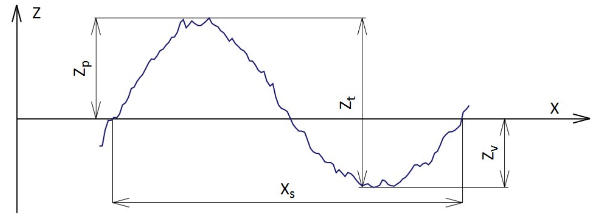

Figure 1. Profile element

Maximum height of the roughness profile Rz is the vertical distance between the highest peak and the lowest valley of the profile. *Arithmetic mean deviation of the roughness profile Ra* and *root mean square deviation of the roughness profile Rq* are, respectively, arithmetic and quadratic means of deviations of all individual profile points from the center line [ISO 4287:1997].

Specifications of profile parameters may call for evaluation of average or maximum parameter values. Use of maximum values is denoted by the suffix –max, average values are denoted by the parameter abbreviation without a suffix [ISO 4288:1996].

When evaluating a surface according to the areal method, a variety of topographical surface features can be identified (Fig. 2). Protrusions above the center plane are referred to as hills, and their highest points are called peaks. Areas below the center plane are known as dales, their lowest points being pits [ISO 25178-2:2012].

Areal surface texture parameters are evaluated on so-called scale-limited surfaces. These include the S-F surface, which is produced by filtering noise and nominal form from the measured surface, and the S-L surface, which is further subjected to Gaussian filtering [ISO 25178-2:2012].

The height difference between the highest peak and the lowest pit is known as *maximum height of the scale-limited surface Sz*. *Arithmetic mean height of the scale-limited surface Sa* is an average of absolute values of Z-distances of all points from the center plane. Similarly, *root mean square height of the scale-limited surface Sq* is a quadratic mean of those distances [ISO 25178-2:2012].

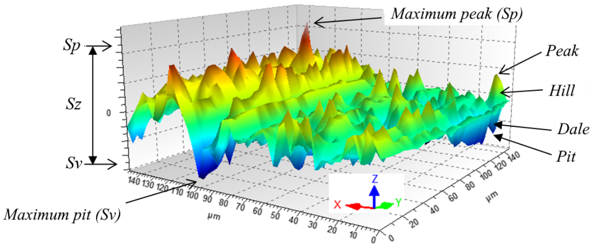

Figure 2. Geometrical features of surfaces [Jankovych 2014]

Profile peaks almost never include the areal peaks corresponding to the measured features. The same applies to profile valleys and surface pits. The probability of passing over the true highest or lowest points during contact measurement is infinitesimally small, and a profile which would include both is practically impossible to achieve. Thus, values of areal parameters can be expected to always be higher, than the values of their profile analogues [ISO 25178-3:2012].

Further differences in values result from the properties of filters used in roughness profile and S-L surface processing. As areal filters work in two perpendicular directions, it is not possible to consider the results of profile and areal filtration equivalent, even if the same filter type and cut-off are used [ISO 25178-3:2012].

3 MEASUREMENT AND EVALUATION OF PARAMETERS

Examination of the relationships between values of profile parameters and their areal equivalents was performed using regression analysis of values of selected parameters on several samples.

A total of 21 samples were included in the study. They were collected from previous studies performed in cooperation with various industrial partners. These included surfaces of parts made of metal, plastics and glass and manufactured by a variety of machining and forming processes. Brief descriptions of the samples and their measurement conditions are included in Tab. 1.

ID	Manufacturing method	Material	Field of measurement [mm]	Filter cut-off [mm]
1	ground	steel	1.66×1.66	0.8
2	ground	steel	1.66×1.66	0.8
3	ground	steel	1.66×1.66	0.8
4	ground	steel	0.83×0.83	0.8
5	ground, worn	steel	0.83×0.83	0.8
6	etched	glass	1.66×1.66	0.8
7	stamped	steel	1.66×1.66	0.8
8	stamped	steel	1.66×1.66	0.8
9	turned	steel	1.66×1.66	0.8
10	lapped	steel	1.66×1.66	0.8
11	etched	glass	1.66×1.66	0.8
12	ground	steel	1.66×1.66	0.8
13	Injection molded, turned	PF resin	1.66×1.66	0.8
14	Injection molded	PPA/glass composite	0.83×0.83	0.8
15	ground	steel	0.83×0.83	0.8
16	sintered	steel	0.83×0.83	0.8
17	ground	steel	1.66×1.66	0.8
18	stamped	steel	2.96×2.96	2.5
19	injection molded	PPA/glass composite	0.83×0.83	0.8
20	cold forged	steel	0.83×0.83	0.8
21	cold forged	steel	0.83×0.83	0.8

Table 1. Samples used in the study

The samples were measured using a Taylor Hobson Talysurf CCI Lite coherence scanning interferometer (Fig. 3). Measurements were carried out using Mirau objectives with 10× and 20× magnification with fields of view of 1.66×1.66 mm and 0.83×0.83 mm respectively. The measurement of sample 18 was performed by stitching together of four adjacent measurements using the 10× objective, resulting in a virtual field of view of 2.96×2.96 mm.

Figure 3. Taylor Hobson Talysurf CCI Lite

As the chosen measuring instrument occasionally produces output with non-measured points, that is points on the X-Y matrix without an associated Z value, these points were filled in using interpolation. The interpolated primary surface was then mathematically levelled in order to correct tilt of the measured surfaces resulting from positioning of the parts during scanning. For samples with non-planar shape, form was removed by least-square fitting of an appropriate geometrical body, producing the S-F surface. In a small number of cases, obvious artifacts consisting of extreme peaks and valleys were manually retouched.

1024 parallel profiles were extracted from each S-F surface with the exception of the larger sample 18, which provided 1826 profiles. These profiles were treated as primary profiles. Thus, all points of the S-F surfaces were used for profile parameter evaluation. Three common roughness parameters, *Ra*, *Rq* and *Rz,* were evaluated on each of the extracted profiles.

Cut-off values for the λc profile filter were initially chosen according to ISO 4288. In ambiguous cases where two different cut-off values produced valid results, the larger value was chosen. Although this procedure was not in total compliance with the abovementioned standard, it eliminates a possible optimistic bias in the parameter values, as described by [Bumbalek 1989], [Whitehouse 1994], [Harcarik 2014]. Most of the samples were evaluated using cut-off values of 0.8 mm, one sample was evaluated with cut-off 2.5 mm.

For areal evaluation, each S-F surface was further filtered using a Gaussian filter with cut-off equal to that chosen for profile evaluation on the respective sample. Parameters *Sa*, *Sq* and *Sz,* philosophical equivalents of the chosen roughness profile parameters, were then evaluated on the resulting S-L surfaces.

4 RESULTS OF THE REGRESSION ANALYSIS OF PROFILE AND AREAL PARAMETERS

Using Minitab, linear models without constant term were fitted to the data. The constant term was left out based on the expectation that an ideally flat surface would present values of all profile and areal surface texture parameters equal to 0, rather than nonzero values separated by an offset determined by the regression model's constant term.

Values of areal surface texture parameters were treated as responses to either mean or maximum values of their profile counterparts. This was done in order to determine, whether so called averaging parameter pairs *Ra*, *Sa* and *Rq*, *Sq* would respond differently than the so called range parameters *Rz* and *Sz*.

Tab. 2 shows the regression coefficients and coefficients of determination obtained from the analysis. Even at a glance, it is clear the fit provided by linear regression is very good in most of the cases, with only one regression model failing to reach R^2 of 0.95.

Relation	**Regression coef.**	R^2
Sa = f(Ra)	1.039	0.987
Sa = f(Ramax)	0.863	0.965
Sq = f(Rq)	1.055	0.985
Sq = f(Rqmax)	0.837	0.963
Sz = f(Rz)	2.158	0.838
Sz = f(Rzmax)	1.298	0.972

Table 2. Regression coefficients and coefficients of determination R^2

Regression fits of arithmetic mean height of the S-L surface *Sa* as a function of arithmetic mean deviation of the roughness profile *Ra* are shown in Figures 4 and 5.

The fit of *Sa* as a function of average values of *Ra* (Fig. 4) is particularly good, with the highest achieved R^2 at 0.987. The only apparent outlier is a sample of conical stamped stainless steel part, which was the only one evaluated with a 2.5 mm filter cut-off.

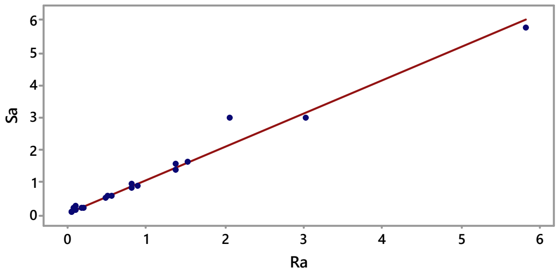

Figure 4. Linear regression of Sa(Ra)

The fit using maximum values of *Ra* (Fig. 5) is somewhat worse, albeit with R^2 still above 0.95. The two outlying values are of a finely ground steel cylinder, and a stamped roughness standard.

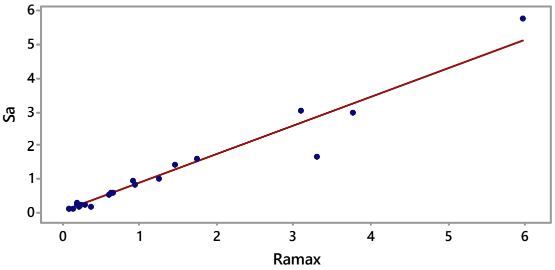

Figure 5. Linear regression of Sa(Ramax)

Regression fits of root mean square height of the S-L surface *Sq* as a function of root mean square deviation of the roughness profile *Rq* are shown in Figures 6 and 7.

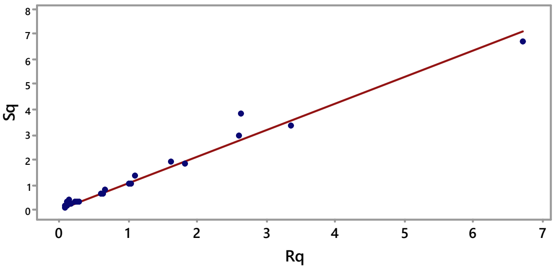

Figure 6. Linear regression of Sq(Rq)

As with *Sa*(*Ra*), the fit for *Sq*(*Rq*) (Fig. 6) was the best, when average values were used, with the second highest R^2 in the study. The outlier again belongs to the sample with highest filter cut-off (2.5 mm).

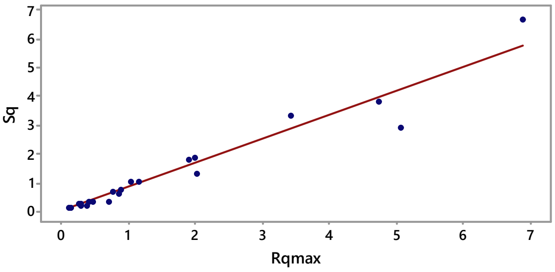

Figure 7. Linear regression of Sq(Rqmax)

The fit for maximum value of *Rq* (Fig. 7) appears more scattered. The two most prominent outliers are the same as in case of *Sa*(*Ramax*).

Finally, regression fits of maximum height of the S-L surface *Sz* as a function of maximum height of the roughness profile *Rz* are shown in Figures 8 and 9.

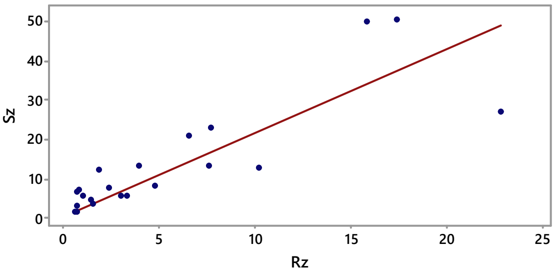

Figure 8. Linear regression of Sz(Rz)

The fit using average values of *Rz* as predictor (Fig. 8) is clearly scattered, with the lowest R^2 of all examined regression models.

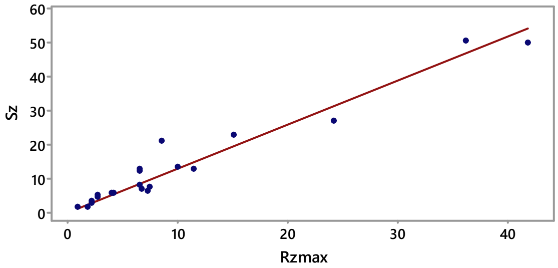

Figure 9. Linear regression of Sz(Rzmax)

On the other hand, the fit using maximum values of *Rz* (Fig. 9) appears somewhat better, with the third best R^2. The furthest outlier was a ground steel sample with signs of friction wear.

5 CONCLUSIONS

Promising fits with R^2 exceeding 0.95 were produced for all the evaluated parameters. For averaging parameters *Ra* and *Rq*, average profile parameter values resulted in the best predictions of areal parameter values. These models also achieved the highest two levels of the coefficient of determination. For the height range parameters *Sz* and *Rz*, the best fit was achieved using maximum values of *Rz* as predictors for areal parameter *Sz* values. The fit was not as good as in the cases of averaging parameters, which is likely a result of *Rz* and *Sz's* sensitivity to extremes.

The results of the analysis indicate that simple mathematical conversion of suggested tolerance values of profile parameters to values for areal parameters may be possible. Nonetheless, optimistic bias may have been introduced as a result of evaluating the profile parameters from data obtained by non-contact measurement, as well as from using all available data points in the profiles.

Further study comparing areal parameter values obtained by non-contact means with a large set of contact profile measurements could be used to determine, whether such a conversion can be deployed industrially. Addition of data from both finer and rougher surfaces, as well as surfaces manufactured by other methods, is also warranted.

In spite of the abovementioned reservations, the regression equations of *Sa*(*Ra*), *Sq*(*Rq*) and *Sz*(*Rzmax*) can, with due caution, be used for choosing areal surface texture specification values of parameters *Sa*, *Sq* and *Sz* on parts, where profile parameter values requiring a λc filter cut-off of 0.8 mm would be indicated.

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