Evaluation of shot peened surfaces using characterization technique of three-dimensional surface topography

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Abstract. Objective parameters to characterize global topography of three-dimensional surfaces have been derived. The idea of this evaluation is to separate the topography into two global form deviations and residual ones according to the degree of curved surfaces. A shot peened Almen strip is measured by profilometer and concrete parameters of inclination and circular-arc shaped global topography are extracted using the characterization technique. The arc height is calculated using the circular arc-shaped part and compared with a value measured by an Almen gauge. The relation between the coverage and roughness parameters is also investigated. The advantage of this evaluation is that it is possible to determine the arc height and the coverage at the same time from single measured topography. In addition, human error can be excluded from measurement results. This method has the wide application in the field of measurement.

1. Introduction

Shot peening is one of the cold-working processes. Many small sized steel or nonferrous metal balls hit onto engineered surfaces at high speed. Then a shot peened surface is deformed non-elastically and has many dimples on it. Because of the plastic deformation, the residual stress is occurred around the peened subsurface. The peened surface becomes harder and has good properties called the "peening effect", for example, longer fatigue strength, improvement of abrasion resistance, and reduction of friction coefficient. Other purposes of shot peening are cleaning, descaling, deburring, etc. The process is widely used in many manufacturing fields.

In order to evaluate the shot peening process, two parameters are normally defined: the "arc height" and the "coverage" using a thin test specimen called Almen strip. The peened Almen strip bends in the circular arc-shaped by the residual stress, and the curving height is measured to evaluate the strength of peening process. The measured curving height is called arc height. The peened surface of the Almen strip has many dimples and the ratio of the area of dimples to the whole surface is defined as the coverage. The arc height is measured with the special measuring equipment called Almen gauge. The coverage is measured with human eyes and evaluated experimentally.

Since the evaluation strongly depends on human subjectivity and is not precise, the authors propose a new evaluation method of the arc height and the coverage in this paper. Surfaces of Almen strips are measured with profilometer in three-dimensions. Measured topography is separated into the circular arc-shaped part of the second order and the residuals using characterization technique proposed by one of the authors. The arc height is determined by the separated circular arc-shaped part and the coverage can be calculated by the residuals using the height information of the surface.
2. Characterization procedure

Characterization of micro topography in two-dimensions and three-dimensions has been performed to find sensitive parameters to analyze the engineering surfaces such as amplitude, spatial and functional parameters [1-3], FFT analysis [4], autocorrelation function [5], fractal analysis [6-9], and so on. There are indeed many parameters proposed, but there is no unified approach [10].

The idea of evaluation and parameters for three-dimensional surface topography in this paper is to separate it into two global form deviations and residual ones as follows[11]:

1. The first order form deviations
2. The second order form deviations
3. The third and higher order deviations

Such separation according to the degrees of the surface makes it convenient to handle the topography mathematically. The separation and calculation of the concrete parameters can be done by the best-fit approximation and least square method; by minimizing the sum of the squares of residuals between deviations as the input data at each separation step and a best-fit function.

3. Best-fit functions

3.1. The first order form deviations

We separate the first order form deviations from original measured topography, which is obtained for example with profilometer in three-dimensions. The first order form deviations should be considered as a plane, which has a meaning of inclination of global topography. Adopting the equation of an arbitrary plane as the best-fit function, the parameters for the first order form deviations can be expressed by the parameters of the plane, namely, three coefficients of the least square plane or the normal vector of it.

Measurement of an Almen strip with profilometer needs to keep it horizontal, but it is impossible to perform perfect horizontal leveling. Using the first order form separation, such a slight leveling imperfection will be eliminated. Subtracting the first order form deviations expressed by the least square plane from original measured topography, we can get the second and higher order deviations, which have no global inclination.

3.2. The second order form deviations

The second order form deviations should be considered as a curved surface, which has the meaning of the curvature and the anisotropy (the nature of direction) of global topography. Adopting the equation of an arbitrary surface of the second order as the best-fit function, the parameters for the second order form deviations can be expressed by the parameters of the surface of the second order.

3.2.1. Definition and the classification of the surfaces of the second order. The general form of an arbitrary surface of the second order is written as follows:

\[ \sum_{i,j=1}^{3} a_{ij} x_i x_j + 2 \sum_{i=1}^{3} b_i x_i + c = 0 \]  \hspace{1cm} (a_{ij} = a_{ji}) \hspace{1cm} (1)

By use of the notations of matrix and vector for the coefficients of the general form expressed by equation (1), we can write,

\[ s(x) = \tilde{x}^T \tilde{A} \tilde{x} = 0 \] \hspace{1cm} (2)

where the symmetric coefficient matrix \( \tilde{A} \) and the vector \( \tilde{b} \) are written together as a \( 4 \times 4 \) matrix and the coordinate vector \( x \) is rewritten as follows:

\[ \tilde{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & b_1 \\ a_{21} & a_{22} & a_{23} & b_2 \\ a_{31} & a_{32} & a_{33} & b_3 \\ b_1 & b_2 & b_3 & c \end{bmatrix}, \quad \tilde{b} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{bmatrix} \]

\[ x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \]

Since equation (2) is a quadratic form and \( \tilde{A} \) is a real symmetric matrix, we can classify the surfaces into the proper forms of the second order by diagonalizing it with an adequate orthogonal
matrix (orthogonal transformation) and by parallel translation [12]. The proper surfaces of the second order are finally reduced to only five fundamental forms using adequate scaling transformation. The final useful classification is shown in Table 1.

Table 1. The classification of the fundamental forms of the surfaces of the second order.

| rank A | sgn A | Name                     | Equation                      |
|--------|-------|--------------------------|-------------------------------|
| 3      | (3,0) ((0,3)) | Ellipsoid               | $x^2 + y^2 + z^2 = 1$         |
| 3      | (2,1) ((1,2)) | Hyperboloid of one sheet | $x^2 + y^2 - z^2 = 1$         |
| 3      | (2,1) ((1,2)) | Hyperboloid of two sheets| $-x^2 - y^2 + z^2 = 1$        |
| 2      | (2,0) ((0,2)) | Elliptic paraboloid      | $x^2 + y^2 = Z$               |
| 2      | (1,1)  | Hyperbolic paraboloid    | $x^2 - y^2 = Z$               |

This is a very important mathematical conclusion. An arbitrary surface of the second order expressed by equation (2) and equation (3) can be transformed into a fundamental form of the second order by the combination of only one rotation (orthogonal transformation), only one parallel translation and only one scaling transformation. In a reverse way, we can express all of the arbitrary surfaces of the second order by transforming adequately five fundamental forms in Table 1 with scaling, parallel translation and rotation.

3.2.2. Best-fit functions for the second order form deviations. According to the classification in the former subsection, the final composition of three kinds of coordinate transformation is expressed as follows:

\[
\begin{align*}
\begin{cases}
  x' = \left(\cos \theta_x x + \sin \theta_y y - Q_z \cos \theta_z - Q_y \sin \theta_z\right)/S_x \\
  y' = \left(-\sin \theta_x x + \cos \theta_y y + Q_z \sin \theta_z - Q_y \cos \theta_z\right)/S_y \\
  z' = (z - Q_z)/S_z
\end{cases}
\end{align*}
\]

(4)

where, $S_x, S_y,$ and $S_z$ are scaling factors, $\theta_\gamma$ is a rotational angle about the Z-axis, and $Q_x, Q_y,$ and $Q_z$ are the components of a parallel translation vector. By substituting the composite transformation into the fundamental forms of the second order, we can obtain the best-fit functions for the second order form deviations. Although there are five fundamental forms of the second order, we can reduce them into two types of the best-fit functions, that is, into paraboloid and ellipsoid/hyperboloid. Since the pages of this paper are not enough, we just show the best-fit function of paraboloid.

\[
z = p_1 (\cos \theta_x x + \sin \theta_y y - Q_z \cos \theta_z - Q_y \sin \theta_z)^2 + p_2 (-\sin \theta_x x + \cos \theta_y y + Q_z \sin \theta_z - Q_y \cos \theta_z)^2 + Q_z = z(x,y)
\]

(5)

The best fitted results as the surfaces of the second order are identified by the combination of the sign of two coefficients $p_1$ and $p_2$ (elliptic or hyperbolic). Using $\varepsilon_i$ for the difference between the surface of the second order $z$ and the second and higher order deviations $\delta_i$ along the Z-direction, we can write,

\[
\varepsilon_i = \delta_i - z(x_i,y_i)
\]

(6)

We can calculate the unknowns so as to minimize the sum of squares of $\varepsilon_i$. The objective function of least square method is as follows:

\[
f(p_1, p_2, \theta, Q_x, Q_y, Q_z) = \sum \varepsilon_i^2
\]

(7)

4. Results and discussions

An example of measured topography and extracted global form deviations of a peened Almen strip is shown in figure 1. Conditions of the shot peening process are also shown in the caption. Measurement of original topography is performed by profilometer with a sampling interval of 10 µm and the sampling number of 500×500.
Figure 1. The whole best-fit results for shot peened surface topography (shot: steel ball of 0.3mm diameter, projection device: centrifugal unit, projection amount: 70kg/m$^2$, average projection velocity: 73m/s).

The results have shown the validity of separation procedure and the derived global parameters. Especially, with respect to the second order deviations, the parameters, from which we can easily imagine the principal curvature and the anisotropy of global topography, have been obtained. Calculated arc height is 0.176mm while a measured value by an Almen gauge is about 0.190mm. Sampling intervals don’t have a great influence on the evaluated arc height. The relation between the coverage and roughness parameters from height information can be investigated.

The advantage of this evaluation is that it is possible to determine the arc height and the coverage at the same time from single measured topography. Those results show that the separation procedure and the derived parameters are very useful to evaluate shot peened topography in practical use.

5. Conclusions
For the purpose of the evaluation of the arc height and the coverage of shot peening process, objective parameters to characterize global topography of three-dimensional surfaces have been derived.

This method can be directly applied to other three-dimensional measured data. Since the difference is only the number of data and sampling intervals, we can utilize this method without changes. It has the wide application in the field of measurement.

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