Physical and Numerical Simulation of Contact Mechanics of Spark-eroded Tool Steel with Controlled Roughness

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Abstract: Spark erosion is a convenient process to produce dies with complex shapes from hard tool materials used under severe contact conditions. A controlled surface roughness can be produced by systematic variation of the milling parameters. This is used in the present work to prepare surfaces for contact mechanics testing and simulation, as will be shown by a newly developed method which performs between contact measurements and finite element simulations of experimentally characterised rough surfaces. In the experiment, the surface roughness of the tool steel is measured by means of optical profilometry. Using an instrumented indentation stage, contact is made with a spherical surface and the force-displacement curve measured. The surface geometry is measured again to detect the effect of plastic deformation. To execute the numerical simulation, the measured surface topography is transferred, one on one, to a finite element mesh with 237169 surface nodes. The method allows to perform precise simulation of the contact of real surfaces, instead of approximate or numerically simulated ones, limited only by the spatial resolution of the measurement.

1 INTRODUCTION

Friction and wear of tool materials are of primary concern in the design and operational of industrial metal forming processes. Despite more than a century of intensive research in this field, it can be stated that a theoretical explanation of friction and wear has not yet been achieved. A first problem to be solved is that of the contact mechanics of rough surfaces. From the first appearance of surface profilers, it was recognised that roughness must be studied from the viewpoint of random process theory (Whitehouse and Archard, 1970; Nayak, 1971). A successful incorporation of this theory into a contact models was made by (Greenwood and Williamson, 1966), who considered a profile consisting of spherical asperities with a Gaussian or exponential height distribution.

These early studies considered “conventional” geometries, in the sense that it was assumed that all the higher moments of the power spectral density exist. More recently, the concept of fractal or self-affine surfaces has gained popularity (Majumdar and Bhushan, 1990; Majumdar and Bhushan, 1991). Using numerical simulation, it is very easy to adapt the classical GW-model to these assumptions.(Müser et al., 2017) present a recent review of existing models which are either based on further refinements of the GW-model or use finite elements, boundary elements or molecular dynamics. The latter three provide a more detailed description of the surface topography. Recent modifications of asperity-based models include new descriptions of the geometry and elastoplastic behaviour (Wen et al., 2018; Yuan et al., 2017), but rely on a statistical analysis of the surface, which inherently implies significant simplification of the real geometry, which is used in this work.

Publications on experimental contact mechanics are relatively rare as compared to studies on simulations and generally rely on certain statistical parameters characterising the roughness, not on detailed analysis of the total geometry. One interesting exception is the study by (Bennett et al., 2017), who used 3D-printing to create surfaces with a

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prescribed topography and observed the contact area through a transparent contacting surface.

Apart from the latter example, in general it is not self-evident to create surfaces with controlled random roughness characteristics. Many surface preparation techniques will generate patterns which are either periodic or strongly anisotropic. Isotropic randomly rough surfaces with controlled roughness parameters have been prepared by sand blasting, electrodeposition and spark erosion. Several authors have shown how the control of electrical discharge parameters can produce surfaces with controlled roughness and fractal parameters (Singh et al., 2004; Deltombe et al., 2014).

2 EXPERIMENTS AND SIMULATIONS

Commercial D2 steel was prepared by spark erosion using an EDM444M3-L numerically controlled electrical discharge equipment with a 15 mm diameter electrolytic copper electrode. For the example presented in this text, a depth of 0.1mm was eroded using 10 ms pulses of 0.8A with a 65% dead time between pulses.

Surface topography was measured by a Nanovea optical profilometer using Chromatic Confocal Technology before and after contact testing. Contact testing was performed on the same system by pressing a spherical stainless steel stylus of 2.5mm radius onto the measured surface at a velocity of 0.25 N/min until reaching a load of 0.5N. According to Hertz contact theory, this allows to maintain the bulk of the sample within the elastic region. The measurement of the surface roughness and surface indentation were centred by creating and indentation in a soft copper specimen and calculating the distance between the centre of the stylus and the centre of the optical pen. This analysis also allows verifying any possible damage to the spherical surface of the stylus by measuring the surface profile of the indentation made in the copper sample.

The measured surface was analysed by means of earlier developed software to determine the fractal dimension (Schouwenaars et al., 2017), roughness and height distributions. The measured geometry was introduced into the ABAQUS Explicit Finite Element Package by creating a mesh with a smooth surface and substituting the height values of the surface nodes with the measured ones. The surface roughness was scaled in such a way that the maximum height difference was equal to 1/2 of the size of the elements used in the contact zone. This procedure is valid if all results are scaled accordingly.

3 RESULTS AND DISCUSSION

The mean square roughness of the surface analysed in this work was equal to 5.8 μm. Its fractal dimension, as determined by the triangular prism method, was equal to 2.8. The bearing curve, i.e. the empirical (cumulative) distribution of the surface heights, is given in Figure 1, both before and after the contact test. Small differences between both curves indicate that some plastic deformation occurred during the test.

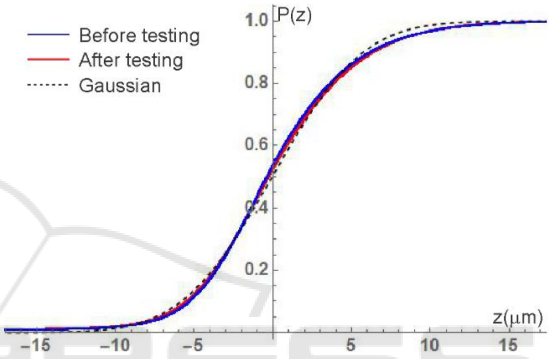

Figure 1: Cumulative height distribution before and after contact testing and Gaussian fit.

Figure 2 presents the measured surface heights before (Figure 2a) and after (Figure 2b) the test. Figure 2c) shows the difference of the height profile before and after testing. To eliminate small shifts in the horizontal position of the measurements, a least-squares procedure was used. No clear pattern can be observed in Figure 2c, indicating that plastic deformation was very small. A low pass filter applied to the three images in Figure 2 revealed that the surface shows a broad maximum in the upper-right quarter of the measured zone which was slightly depressed as the consequence of plastic deformation during the test. This small difference is also seen in the height distributions of Figure 1.

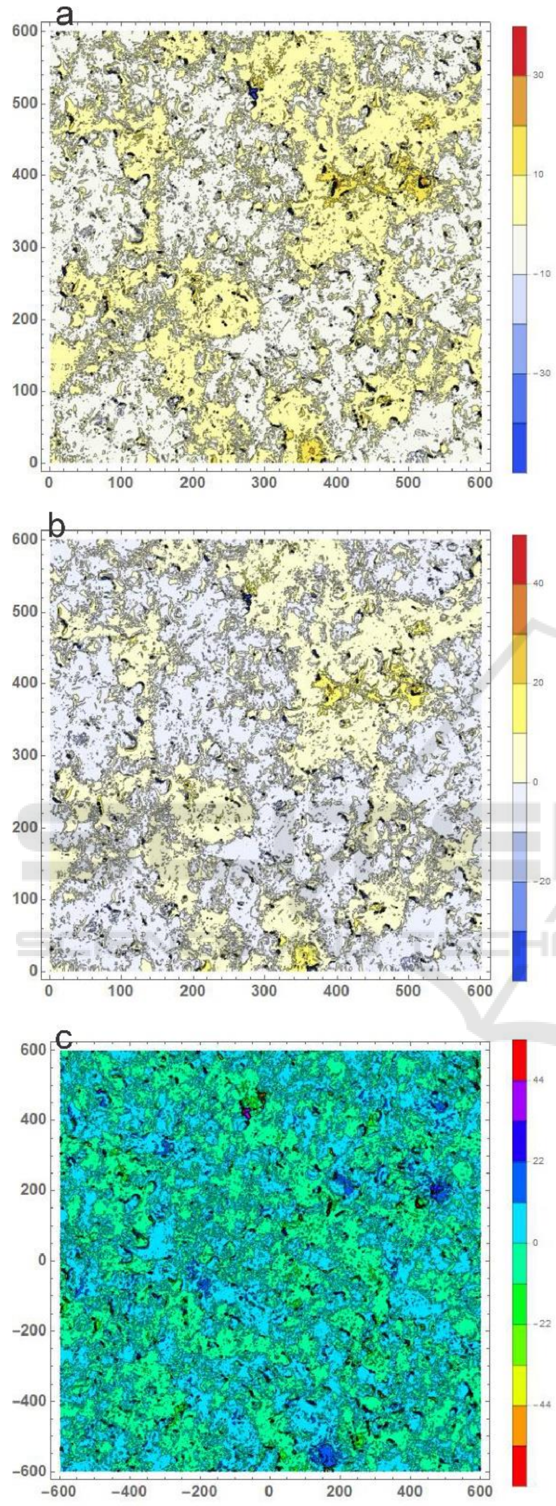

Figure 2: a) shows the surface profile before testing, b) shows the same after testing, c) gives the height differences due to the indentation. The difference pattern is almost random, with a slight tendency to negative values, indicating only small plastic effects were present.

An example of the finite element results is given in Figure 3. Figure 3a shows the raw load-displacement curve after scaling. Some initial fluctuations are due to the explicit integration scheme, the small load before contact corresponds to the weight of the contacting body. The point of first contact occurs at a displacement of 24.9 µm in the model.

Figure 3b shows the experimental loading and unloading curves, with evidence of a small plastic deformation, as the unloading curve is shifted to the left. The point of first contact occurs at approximately 12.8 µm. Applying the appropriate shifts allows comparing model to experiment.

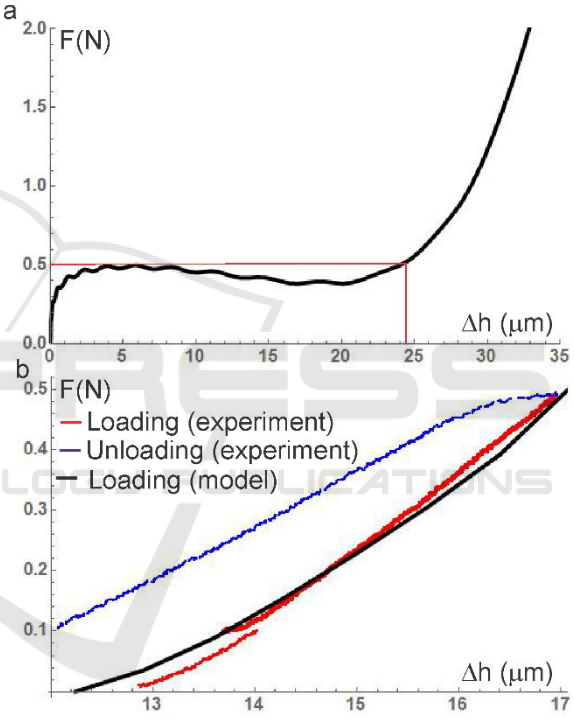

Figure 3: a) shows the modelled curve without correction for dynamic effects and instrument weight. b) compares the corrected curve to the measured ones. The shift applied to obtain Figure 3b is marked by the red reference lines in 3a.

Figure 4 shows the contact pressure distribution. 4a corresponds to the situation at maximum load (0.5N, true indentation depth equal to 4.8 µm) as shown in Figure 3b. It is seen that only a small number of asperities contacts the spherical stylus. 4b is added to provide a clearer view of how such a contact distribution looks at higher loads. The image corresponds to an indentation depth of 40 µm. Evidently, considerable plastic deformation would occur at these loads, which is not taken into account in the present simulations but can be incorporated into future experiments and models.

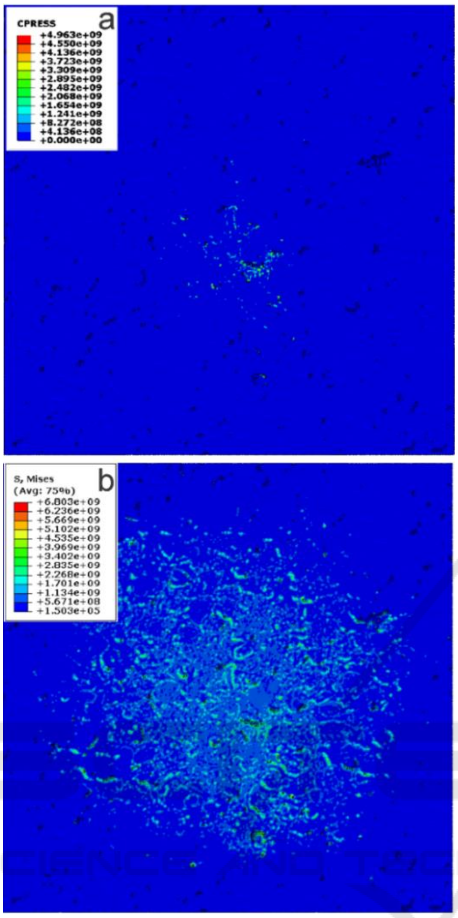

Figure 4: Contact pressure distribution as predicted by the model at an indentation depth of 4.8 μm (a) and 40μm (b).

4 CONCLUSIONS

Spark erosion can generate randomly rough surfaces with controlled roughness and a high fractal dimensions. Combining standard equipment for instrumented indentation with an optical surface profiler mounted on the same console, precise measurements of contact load-displacement curves can be combined with a detailed analysis of the surface topography before and after testing.

Using purposely developed software, the measured surface can be superposed on a pre-existing finite element mesh. The measured geometry and the finite element geometry are the same, the only limitation is the spatial resolution of the measurement. This is a significant innovation and can be used in future, more extensive studies in which the surface roughness will be varied through systematic analysis of the electric discharge parameters.

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