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Study of contact of rough surfaces: Modeling and experiment

Stanislaw Kucharski*, Grzegorz Starzynski

Institute of Fundamental Technological Research, PAS, Warsaw, Poland

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ABSTRACT

In the paper a problem of contact of rough surface with rigid flat plane is investigated experimentally and numerically. Samples made of three different steels with roughness constituted in a sand-blasting process were compressed in a special experimental setup. 3D surface topographies were measured in initial and deformed state using scanning profilometry. An experimental procedure has been designed that enables specifying load-approach and load-real contact area relations corresponding to plastic deformation of roughness zone. These relations were also simulated using a simple model based on statistical approach with special procedure proposed for a proper specification of sampling interval. The experimental and numerical results have been compared.

1. Introduction

The topographies of interacting surfaces can have a significant influence on the global physical and mechanical behaviors of a technical system. The evaluation of real contact area between two rough surfaces is an important issue for understanding tribological quantities and processes such as friction, wear, adhesion, lubrication, air or water leakage [1]. The relation between the thermal and electromagnetic resistivity and real contact area between two solids in contact is also important [2,3,4].

It is well known that roughness features can be defined in a wide length scale ranging from the length of physical sample to atomic scale. To study the mechanism of any contact problems, it is necessary to characterize such multi-scale rough surface and to know the structure at length scale to the examined phenomenon. The modeling of the relevant contact between two rough surfaces consists of two parts: the first is geometrical – the modeling of topography of surface, and the second is mechanical – modeling of deformation of asperity. Combination of these two models can give a general description of contact of two rough surfaces.

One of the most developed ideas of describing surface topography are the methods of defining roughness using random process theory. Many statistical parameters can be computed from mathematically modeled surfaces. The distribution of surface summits (defined as the point having a greater height than those of the four or eight neighbors) is frequently assumed to be Gaussian.

On the basis of probability theory, following the many surface theoretical works, Greenwood and Williamson [5], Nayak [6,7], Whitehouse and Archard [8], and Greenwood [9] have made an important advancement in developing the model of the contact of rough surface. When Greenwood and Williamson [5] formulated their original description of elastic rough contact, they based it on the assumption that only asperity height was a random variable, and the radius of each spherical peak was constant, and they used the Hertz solution of elastic deformation of sphere in rigid half-space. Greenwood and Trip [10] expanded the model in 1970 to the contact of two rough surfaces and concluded that the contact between two rough surfaces is not significantly different from the contact between a rough surface and a flat plane.

One of the drawbacks of this class of models, which rely on the specification of a single radius of curvature, is the ambiguity of scale. That is, the determination of the average radius of curvature of a surface profile is sensitive to the scale of observation, or more specifically, to the lateral resolution used to measure the surface. The GW theory assumes roughness on a single length scale, which results in an area of real contact which depends (slightly) non-linearly on the load even for very small loads. Bush et al. [11] have developed a more general and accurate contact mechanics theory (BGT) where roughness is assumed to occur on many different length scales. This results in an area of real contact which is proportional to the squeezing force for small squeezing forces. Important considerations relating to the linearity of the real contact area–load have been proposed in [12], considering not only the asymptotic Bush–Gibson–Thomas (BGT) solution for very small loads, but also the full solution, giving rise to a deviation from linearity in the intermediate and high pressure regimes. In 2006 Greenwood additionally simplified the (BGT) contact model but obtained very similar results [13]. All of these

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* Corresponding author: Tel.: +48 22 8261281 141; fax: +48 2282677380
E-mail address: skuchar@ippt.pan.pl (S. Kucharski).

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models concerned the description of surface roughness described by the single selected profile.

The statistics of Greenwood models [5,9] framework has been preserved, but different models are implemented for the asperity deformation. The GW model and generally their idea are widely used and being modified up till now. In recent years, Greenwood with other authors developed the GW theory by introducing the interaction between asperities [14], and also evaluated the difference between the approaches of two and three dimensions. They concluded that the mean real contact pressures calculated for two dimensions will be much lower than in three dimensions, and will depend strongly on the thickness of the “slab” used to represent the elastic half-space [15].

Various extensions of the GW contact model have been developed to incorporate effects of adhesion and plastic deformation [16,17]. With only a small fraction of the available area supporting the load, the contacting asperities of the surfaces often carry very high compressive stresses. These high stresses will often cause yielding in the material and thus purely elastic contact models of rough surfaces are not always adequate. Chang at al. [16] modified the GW theory by introducing the plastic deformation of the most highly loaded asperities. Buczkowski and Kleiber (1999) [18] proposed a random surface model of elasto-plastically yielding asperities with Gaussian height distribution combined with mechanical description of a single peak based on the Hertz theory coupled with the Mindlin friction theory. The stochastic model was included in a incremental finite element procedure. A few years later authors extended their model and presented the complete elasto-plastic microcontact model of anisotropic rough surfaces [19].

Whitehouse and Archard [8] extended the random asperity model to include random heights and curvatures. In the model the assumption is used that any surface profile of random type can be completely defined (in statistical sense) by two characteristics: the height distribution and the autocorrelation function. In their theory for the first time the important problem appears – asperity density and curvatures and some others parameters resulting from random theory are not intrinsic properties of the surface, and depend on the correlation distance (and, indirectly, on sampling intervals). However, Archard's contact model is based on hypothetical, idealized surfaces and is difficult to apply to a real rough surface. Again, the rough surface was described by a random profile, related only to the model geometry, and did not include contact mechanics. This was in 1970 but the problem came back in the work of Greenwood (2001) [21], where the authors criticize their own proposition and definition of asperities. They claim that peaks or summits defined according to the previous definition do not represent the asperities and correspond to artifacts at the surface, especially when a small sampling interval is used. It is not hard to imagine that there will be a lot of peaks that will conform with the 3-point definition, but from the point of view of the mechanical contact it will be completely irrelevant. Also Thomas [20] and Thomas and Rosen [22] proposed the determination of the optimum sampling interval for rough contact mechanics 30 years after the paper of Whithouse and Archard, so, it is seen, the problem is not trivial. They presented the relationship of relevant roughness parameters to properties of the power spectral density function (PSDF). Then they expressed the PSDF in terms of fractal parameters, which are independent of condition of measurement. The last part of the model is to combine the plasticity index based on slope with second moment equation of PSDF and they obtain the relationship between the critical wavelength, fractal dimension and material properties. This approach is limited to the Gaussian distribution of heights of the surface and power spectra as a power law.

Recently some experimental works appeared showing the influence of both the definition of peak and sampling interval [23–26]. Different criteria that take into account the number of required neighboring points on the profile (i.e., 3, 5 and 7 points), the peak-threshold value (z-direction) and the effect of the data resolution in the x-direction were applied in this study. The results show the huge influence of these pre-selected criteria for which no verified guidelines exist.

In recent years there has been a return to the description of the surface and contact mechanics based on the profiles. In a large two-part work by Pugliese, Ciulli, and Ferreira (2008) [27], the authors presented several ways to approximate the roughness profile through a set of parabolas, based on the approach of Aramaki [28]. This is a clear attempt to describe the asperities, avoiding the problem of measuring resolution. The real profile is described by parabolas that simulate it by maintaining the constancy of some specific characteristics (approach of same area, same Rq, least mean squares (LMS), etc.). The contact mechanics models used include two different elastic ones and two elastic–plastic models (Chang et al. [16] and Zhao et al. [17]). The combination of this approach with the contact mechanics model including the elastoplastic transition developed by Zhao, Maietta and Chang seems to guarantee the best results. However, it seems that the authors have committed some inaccuracy in describing the surface with a profile (2D) and used the mechanical solutions for three-dimensional solids.

Some authors presented a completely different approach to solving the problem of contact of rough surfaces. More recently, Buchner et al. [29] developed a new concept based on a combination of the bearing area curve and a model asperity representing the average asperity slope of the original surface profile (after Hansen [30]). This paper presented a method for evaluating the real contact area depending on the normal load that takes the material properties and real asperity slopes into consideration, and simplification is achieved by making use of the original character of real surfaces. The deformation of the bearing area curve and the Hansen profile were calculated by finite element analysis. For a given remaining height the real contact area and total normal force were determined. The new concept showed very good correspondence with the data obtained by FEM simulating the compression of the original profile of tested sample.

Another new method to determined the contact between rough deformable surface and rigid smooth plane has been investigated by Belghith et al. in the work [31]. Roughness parameters for the microscopic model were deduced using the standard procedure for roughness and waviness “motif” parameters. The “motif” is defined as the part of the profile found between two peaks. This study described asperity geometry by Robbe-Valloire's approach [32], which assumes a perfect circular shape of asperities radius with a lognormal distribution. The new idea was to determine the mean radius of asperity from dimensional characteristics of each motif. Results of deterministic microscopic model have been validated with an analytical study and a good correlation is found.

In this paper the analysis of surface topography is presented in the context of investigation of contact of rough surfaces. In particular the problem of sampling interval in surface topography measurements is considered. The influence of sampling interval on some roughness parameters that are important in contact process is studied. A simple model of contact is proposed and verified experimentally.

2. Experiment

The experiment was consisted of 4 stages:

- specification of stress–strain curves for selected steels,
- measurement of surface topography of constituting rough surfaces before contact loading,
- contact loading and measurements contact compliance p–a, and