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Influence of surface roughness on dispersion forces

V.B. Svetovoy [a,*], G. Palasantzas [b]

[a] MESA+ Institute for Nanotechnology, University of Twente, PO 217, 7500 AE Enschede, The Netherlands
[b] Zernike Institute for Advanced Materials, University of Groningen, 9747 AG Groningen, The Netherlands

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ABSTRACT

Surface roughness occurs in a wide variety of processes where it is both difficult to avoid and control. When two bodies are separated by a small distance the roughness starts to play an important role in the interaction between the bodies, their adhesion, and friction. Control of this short-distance interaction is crucial for micro and nanoelectromechanical devices, microfluidics, and for micro and nanotechnology. An important short-distance interaction is the dispersion forces, which are omnipresent due to their quantum origin. These forces between flat bodies can be described by the Lifshitz theory that takes into account the actual optical properties of interacting materials. However, this theory cannot describe rough bodies. The problem is complicated by the nonadditivity of the dispersion forces. Evaluation of the roughness effect becomes extremely difficult when roughness is comparable with the distance between bodies. In this paper we review the current state of the problem. Introduction for non-experts to physical origin of the dispersion forces is given in the paper. Critical experiments demonstrating the nonadditivity of the forces and strong influence of roughness on the interaction between bodies are reviewed. We also describe existing theoretical approaches to the problem. Recent advances in understanding the role of high asperities on the forces at distances close to contact are emphasized. Finally, some opinions about currently unsolved problems are also presented.

Contents

* Corresponding author.
E-mail address: v.svetovoy@utwente.nl (V.B. Svetovoy).

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1. Introduction

Dispersion forces originate from quantum and thermal fluctuations of electric currents inside of interacting media and in the gap separating them [1–4]. Assuming flat surfaces, the forces increase as $d^{-\alpha}$ when distance d between bodies decreases. The exponent α is in between 3 and 4 depending on the distance. Conditionally the dispersion forces become dominant when the bodies are separated by the distances smaller than 100 nm. They play an important role in nanoscience and nanotechnology including micro and nanoelectromechanical devices [5–8]. The role of these forces is also essential in colloid and interface science [9–15]. In the latter case the interaction happens in a liquid medium, where in addition the electrostatic forces are involved. The dispersion forces are closely related to adhesion between bodies under dry conditions [16,17]. They define the adhesion energy as the force acting via the gap separating the bodies upon contact.

Historically different names are used for the forces, which we call here dispersion forces. At distances smaller than a few nanometers these forces are termed van der Waals forces [1]. At larger distances the same forces are called the retarded van der Waals forces or Casimir forces [2,19]. All these forces have the same physical origin related to fluctuating currents. To stress this point the general name Casimir–Lifshitz force is in use. Evgeny Lifshitz [3] was the first who recognized the common origin of the van der Waals and Casimir forces. He deduced the so-called Lifshitz formula [18], which is able to predict the force between two parallel plates separated by distance d using as input parameters the dielectric functions of interacting materials. Therefore the bodies within the Lifshitz theory are treated macroscopically. The minimal size in the Lifshitz theory is the size where the dielectric function is well defined (much larger than interatomic distances). The Lifshitz formula interpolates between the van der Waals force at small distances $d < 5$ nm and the pure Casimir force at $d > 1$ μm. Between parallel plates the first decreases as d^{-3} while the second one decreases as d^{-4} when the distance increases. In this paper to name all the forces having the same origin we use the general term dispersion forces proposed by London for molecules.

The dispersion forces are nonadditive. The force between two molecules depends on the position of a third molecule located nearby. A consequence is that the force between bodies of finite size cannot be calculated as pairwise summation of forces acting between separate molecules. This is an important point because it complicates the calculation of the force in many practical situations. Nonadditivity is often cited as a very specific property of the dispersion forces. However, the electrostatic force can also be nonadditive. The force between metallic sphere and plate cannot be calculated as the sum of forces between infinitesimal capacitors. The reason is that the charges redistribute in response to the field. A similar effect happens for the dispersion forces where polarization changes with the field.

One limitation of the Lifshitz formula is that the force is predicted explicitly only between parallel plates. It is not a principal restriction but rather a computational one related to nonadditivity. Only recently a closed-form expression for the sphere–plate interaction was presented [20,21]. Even for numerical calculations the problem was not an easy task but significant progress was made in the last decade and the force was evaluated for a number of geometrical configurations [22]. The same restriction exists for the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory of colloidal stability [9,10] with an additional complication that includes electrostatic forces.

Nonadditivity makes the problem even more difficult if one would like to calculate the force between randomly rough bodies. All solids in nature or in laboratories are rough. The roughness can be characterized by two main parameters that are the root–mean–square (rms) roughness ξ (typical feature size). While w is much smaller than the distance between bodies d the roughness correction to the force can be calculated using the perturbation theory. The corresponding methods have been developed in relation to the precise measurements of the Casimir forces at distances larger than 100 nm [23–25]. However, when the force was measured at distances smaller than 100 nm, strong deviations from the predictions based on the perturbation theory were found [26] even for relatively small rms roughness $w \ll d$. As was explained later [27] this effect is due to significant deviations of the roughness statistics from the normal distribution for some materials.

The ultimate problem related to surface roughness is the evaluation of the force when the rms roughness is comparable with the distance between the bodies. At this moment the problem is not solved but it is clear that high peaks of the roughness profile play a principal role. For this reason the problem is closely related to the contact between two bodies. In principle the force can be calculated numerically, but practically it can be done only for a restricted area. Up to now the roughness effect was not tackled numerically. The important role of high peaks, which are rare statistical events, combined with numerical calculations and experimental data could give a strong push to understand the influence of roughness on dispersion forces.

The purpose of this paper is not only to review existing experimental and theoretical approaches to the roughness problem, which are still in their infancy, but also to give an introduction for non-experts to the methods used to calculate the dispersion forces in different practical situations. The paper is organized as follows. In Section 2 the physical origin of the dispersion forces is described and some helpful relations are presented. A review of experiments important for understanding of the roughness effect is presented in Section 3. Methods to describe rough surfaces and existing theoretical models for the force taking into account roughness effect are described in Section 4. Finally some conclusions and our vision of the problems that have to be solved are collected in the last chapter.

2. Dispersion forces

In this section we describe the main ideas and results of Lifshitz theory of dispersion forces. We try to present a clear physical picture and give the necessary equations in the form convenient for practical applications of the theory. This section can be considered as an introduction to the Lifshitz theory. Quite often it is not realized that so different physical phenomena as well-known van der Waals forces acting between macroscopic bodies separated by a few nanometers gap and rather