Powder Technology 312 (2017) 321–333

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

The influence of surface roughness and adhesion on particle rolling

R. Wilson[a,*], D. Dini[b], B. Van Wachem[b]

[a] *Department of Physics, The Blackett Laboratory, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom*
[b] *Department of Mechanical Engineering, City and Guilds Building, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom*

A R T I C L E I N F O

Article history:
Received 15 September 2016
Received in revised form 25 January 2017
Accepted 28 January 2017
Available online 1 February 2017

Keywords:
Rolling resistance
Discrete element model
Surface roughness
Adhesion

A B S T R A C T

The influence of surface roughness and contact adhesion on the rolling behaviour of dry particles has been investigated. Rough particle surfaces are approximated using an array of spheres, the properties of which are informed by random processes. An analytical model has been derived by considering the torques that a particle experiences. Two mechanisms of rolling resistance are explored – a stationary particle experiencing a tangential force, and a dynamically rolling particle. The analytical model is found to agree well with simulations of the equivalent system using the discrete element model. Adhesive forces are found to increase rolling resistance in all cases. The complex consequences of varying the height variance and length scale of the surface roughness are reproduced accurately by the analytical model.

1. Introduction

Many industrial and natural processes involve granular systems. Diverse phenomena such as avalanches [1], fluidized beds [2] and asthma inhalers [3] all depend on assemblies of small particles. However, due to the subtlety of interactions between the constituent grains, the behaviour of granular systems is complex and can be difficult to predict. Gaining a better knowledge of the mechanics of granular systems is therefore critical to the development of industrial processes, and the understanding of natural phenomena. Moreover, one would like to develop simple tools to study such systems, although some of the models required by these tools do not yet exist, or are not yet sufficiently accurate.

Real particles will always exhibit a degree of surface roughness. This has the effect of modifying the contact forces experienced during collisions [4], and can have a significant effect on the motion of a particle. Roughness is a phenomenon which typically occurs over many length scales [5]. Depending on the material, and on processes which have been applied to the surface, it is possible for a surface to exhibit roughness down to the atomic scale. Due to the wide range of forms that a rough surface may take, it is difficult to generalise the effect of roughness on a contact.

Of particular interest in this study is the behaviour of fine powders. The influence of adhesive forces on a particle can be found in the ratio of adhesive force ($\propto$ surface area) to weight ($\propto$ volume). A system of smaller grains will therefore experience more significant adhesive interactions. For dry powders with grains below $\sim$ 100μm Van der Waals interactions can no longer be treated as negligible [6]. In such cases the powder cannot flow as freely. This leads to behaviour such as bubbling in fluidized beds [2,6], and agglomeration [7].

It has relatively recently become possible to perform detailed simulations of granular flows. Frequently used methods include the Discrete Element Model [8] (DEM), or the treatment of particles as a continuous Eulerian phase [9]. In the present study, DEM is employed. It was chosen because it allows the physical properties of grains to be easily varied, and allows for relatively complex models to describe interactions on the scale of individual particles. The behaviour of a system is often strongly dependent on the interactions between grains, such that small changes on the particle scale can lead to large differences in system behaviour. It is therefore useful to know which properties are most influential, and to simulate them accurately.

In this work we focus on the resistance to rolling motion. Rolling resistance is critical to the behaviour of certain types of granular system. Sand piles, for example, can be strongly influenced by the magnitude of rolling resistance between particles. [10]. Additionally critical phenomena such as avalanches can be related to the presence of mechanisms which encourage collective, rather than individual, motion of particles – for instance friction and rolling resistance [11]. In particular, we study the influence of surface roughness and adhesive interactions on particle rolling.

1.1. Causes of rolling resistance

One factor that makes rolling resistance difficult to investigate is that a number of mechanisms may contribute to the observed

* Corresponding author.
E-mail address: robert.wilson12@imperial.ac.uk (R. Wilson).

http://dx.doi.org/10.1016/j.powtec.2017.01.080
0032-5910/

phenomena. Any interaction which leads to an asymmetry in contact forces as a particle rolls may result in a torque which resists the rolling. The processes which most commonly lead to this situation are discussed presently.

Rolling resistance of a sphere may arise due to visco-elastic dissipation in the contact. This effect has been studied in detail, both analytically and using FEM simulations [12–15]. The visco-elastic force opposes the normal motion in the region of contact. As a sphere rolls on a plane, one half of the contact will be moving towards the plane, while the other half moves away. A torque is therefore induced by the opposing visco-elastic forces on either side of the contact. The same visco-elastic forces are responsible for energy dissipation during collisions, leading to a relationship between the collision dynamics and rolling behaviour of a sphere [15].

Contact plasticity may also play a part. In this instance the shape of either the particle, or the surface on which it rolls, is permanently deformed. Both cases lead to an extra 'bump' which the particle must surmount to continue rolling. This leads to an asymmetrical stress distribution when the particle rotates by a small amount, and therefore a torque. It has been observed that repeated rolls of a steel ball over the same surface of softer metal result in a decrease in rolling resistance. [16] This is consistent with the expected behaviour of rolling resistance due to plasticity, as the process of strain hardening reduces plastic deformation when the same area is repeatedly rolled over.

A third mechanism is adhesion, which can lead to energy dissipation while rolling. In the case of soft particles with large surface energies, there is a hysteresis effect as the particle comes in and out of contact. This is described by, for example, the Johnson-Kendall-Roberts (JKR) contact model [17]. The difference in force as the particle leaves contact leads to an energy dissipation associated with breaking adhesive bonds. The effect of this phenomenon on a rolling sphere has been taken into account [18,19], and found to result in a critical torque which must be applied before rolling occurs. When the adhesive energy is small compared to the energy required to cause significant elastic deformation there is no hysteresis; however, the additional normal force will modify the effects of viscoelastic and plastic interactions.

Finally, as a fourth mechanism, particle shape influences the rolling behaviour [20]. Stationary non-spherical particles may experience torques which resist applied tangential forces. Surface roughness does not introduce any dissipation, however can interact with other mechanisms to change the dissipation during rolling. For example, the moment induced by viscoelastic effects depend on the shape of the contact area.

In the present study we investigate the resistance to rolling due to the interplay between particle shape effects and adhesion. The focus is on rough, approximately spherical, grains. By characterising the roughness, we have developed analytical models to describe the torques experienced by a particle as it begins to roll, and in the case of a dynamically rolling particle. It is found that as well as shape and adhesion, viscoelasticity plays a significant role in some cases. These models are compared to numerical simulations of the equivalent rough particles, and the results discussed.

2. Theory

A number of models have been applied to spherical particles to describe the torque of rolling resistance, τ_r. Various assumptions on the mechanisms of energy dissipation and the source of torques lead to a number of analytical forms. The three most commonly used models are summarised below. Models tend to contain a coefficient of rolling resistance, μ_r, along with terms containing the particle radius, R, normal force, F_n, and angular velocity, $\boldsymbol{\omega}$.

A constant torque, opposing the rolling motion of the particle was proposed by Beer and Johnston [21]:

$$\boldsymbol{\tau}_r = -\mu_r R F_n \frac{\boldsymbol{\omega}}{|\boldsymbol{\omega}|}. \tag{1}$$

This form of rolling resistance has been used to study, amongst other things, the formation of sand piles [10,22]. While the behaviour of spheres is found to match well to experimental results, this model has the disadvantage that it leads to angular velocities which oscillate around $\boldsymbol{\omega} = 0$.

A second model treats rolling resistance as a damping effect. In this case the rolling resistance is proportional to the rate of rolling, as shown in Eq. (2), and leads to the exponential decay of $\boldsymbol{\omega}$. This analytic form can be found by investigating the viscous forces in a contact [12].

$$\boldsymbol{\tau}_r = -\mu_r R F_n \boldsymbol{\omega}. \tag{2}$$

An expression of this form is more stable than the constant torque model, as $\boldsymbol{\omega}$ is guaranteed to tend towards zero. However, according to the simulations of Zhou et al. [10] the behaviour of a sand pile using this model is not as realistic as that using the constant torque model of Eq. (1).

The third commonly used model takes a form similar to the Mindlin-Deresiewicz [23] model commonly used to model the frictional behaviour of spheres. A resistive torque initially increases linearly with the angle rolled, ϕ_r, with a constant of proportionality k_r. Upon reaching a threshold value, the torque is constant. These expressions are shown in Eq. (3).

$$\boldsymbol{\tau}_r = \begin{cases} -k_r \phi_r \frac{\boldsymbol{\omega}}{|\boldsymbol{\omega}|}, & \text{if } |\boldsymbol{\tau}_r| < \mu_r R F_n \\ -\mu_r R F_n \frac{\boldsymbol{\omega}}{|\boldsymbol{\omega}|}, & \text{otherwise.} \end{cases} \tag{3}$$

This model may also include a dissipative term of the form shown in Eq. (2). Without a dissipative term, this model tends to oscillate in a similar manner to the constant resistive torque shown in Eq. (1). These models have been compared in detail by Ai et al. [24].

A shortcoming of many existing models is that they rely on the coefficient of rolling resistance as a parameter, rather than prescribing a coefficient based on physical properties of the particles. It is frequently the case that the model is based on unrealistic assumptions – *e.g.* perfectly spherical particles – or must be fitted to experimental data. By considering particles with less idealised geometrical properties, the results of the current paper provide a better understanding of the influence of roughness and adhesion on rolling resistance.

2.1. Modelling of rough surfaces

A number of factors contribute to the geometry of a surface, including the chemical composition of the material, the method used to form the surface, and subsequent processes it may have been subject to. In order to model a generic rough surface, it is necessary to apply a number of constraints, as no mathematical model can describe every possible roughness. Several mathematical approaches have been developed [4,25-27] to describe rough surfaces.

Under light loading, contact between surfaces is made only at the peaks of the roughness profile. Models such as the Greenwood-Williamson [28] (GW) and Bush-Gibson-Thomas [25] model take advantage of this fact, approximating the asperities as spherical or ellipsoidal, and thereby greatly simplifying the contact problem. The Greenwood-Williamson model – a particular focus of the present study – treats asperities as spheres with a Gaussian distribution of heights. An alternative approach is to model the surface using random process theory [26]. In this case the statistical properties of a surface such as the average gradient and curvature may be derived analytically.

In the present study, surfaces are described using a model which is conceptually similar to the Greenwood-Williamson model. A rough surface is described using spherical asperities. Rather than consider the average loading behaviour of many asperities on a plane, we