Journal of Physics and Chemistry of Solids 77 (2015) 92–100

Contents lists available at ScienceDirect

Journal of Physics and Chemistry of Solids

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

A numerical study of the mechanical behavior at contact between particles of dissimilar elastic–ideally plastic materials

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ARTICLE INFO

Article history:
Received 13 May 2014
Received in revised form
18 August 2014
Accepted 29 August 2014
Available online 16 October 2014

Keywords:
Alloys
Metals
Mechanical properties

ABSTRACT

In the present study contact between elastic–ideally plastic dissimilar spheres are investigated in detail. The investigation is based on numerical methods and in particular the finite element method. The numerical results presented are discussed with respect to correlation of global contact properties as well as the behavior of local field variables such as contact pressure distribution and the evolution of the effective plastic strain. Large deformation effects are accounted for and discussed in detail. The constitutive behavior is described by classical Mises plasticity. It is shown that correlation of the dissimilar contact problem can be accurately achieved based on the Johnson contact parameter with the representative stress chosen as the yield stress of the softer material.

1. Introduction

It is of great importance in many technical applications to study the mechanical behavior when two or more bodies come in contact with each other. Examples of such applications include gears, rollers and bearings. Contact often gives rise to high stress concentrations which in turn can lead to plastic deformation and/or cracking, or crack growth. The load-bearing capacity of a structure can then be reduced significantly. Another area where knowledge of contact mechanics is of significant importance is in case of indentation or hardness test. In such an experiment the constitutive properties of the material are determined from an impression in the form of a ball, flat punch or pyramid, which is pressed into the material and quantities like hardness, defined here as the average contact pressure, and contact area are measured.

Most often, an advanced contact mechanics analysis is needed in order to interpret the results from an indentation test and also to understand the other contact problems mentioned above. Arguably, contact mechanics as a particular subject within solid mechanics started with the famous analysis by Hertz [1] where the problem of contact between two (locally) spherical glass lenses was studied based on the assumption of predominantly elastic deformations. After that, contact mechanics have reached quite a maturity as a research subject and attracted a considerable amount of attention from numerous researchers all over the world. It seems pretentious to make a complete overview of the subject in this context and for this reason, only the classical contributions by Tabor [2] and Johnson [3,4] should be mentioned here.

Depending on the material properties and the type of indenter used, Johnson [3,4] suggested that the outcome of an indentation test on classical elastoplastic materials could be placed in one of three levels as specified by the parameter

$$\Lambda = \frac{E \tan \beta}{(1-\nu^2)\sigma_{rep}} \tag{1}$$

where E is Young's modulus and ν is Poisson's ratio, β is the angle between a sharp indenter and the undeformed surface while for a ball indenter $\tan\beta \sim (a/R)$ with a being the radius of the contact area and R the radius of the indenter. Furthermore, σ_{rep} is the material flow stress at a representative value of the effective (accumulated) plastic strain ε_{rep}. As for the three indentation levels, schematically shown in Fig. 1, Level I, $\Lambda < 3$, corresponds to the occurrence of very little plastic deformation during indentation testing, meaning that all global properties can be derived from an elastic analysis. In level II, $3 < \Lambda < 30$, an increasing amount of plastic deformation is present and both the elastic and plastic properties of the material will influence the outcome of the test. It was shown by Johnson [3,4] that in this region, the material hardness H, here and in the sequel defined as the average contact pressure, relates to Λ as

$$\frac{H}{\sigma_{rep}} \sim \ln \Lambda \tag{2}$$

Finally, in level III, $\Lambda > 30$, plastic deformation is present over the entire contact area. The last mentioned level is applicable to most engineering metals at high or moderate loading. From a number of

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http://dx.doi.org/10.1016/j.jpcs.2014.08.016
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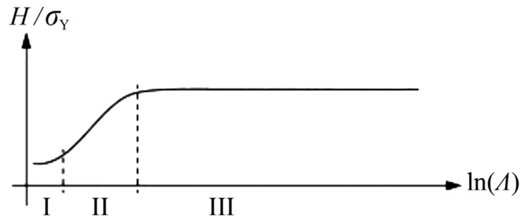

Fig. 1. Normalized hardness, H/σ_{rep} as a function of ln Λ, Λ defined according to Eq. (1). Schematic of the correlation of indentation testing of elastic–plastic materials as suggested by Johnson [3,4]. The three levels of indentation responses, I, II and III, are also indicated.

tests performed on different materials pertinent to level III, Tabor [2] concluded that a simple formula relating hardness H, flow stress and a constant, dependent on the geometry of the indenter, could be derived according to

$$H = C\sigma_{rep} \tag{3}$$

It should be immediately emphasized that the indentation results above can also be used for analyzing more general contact problems between two bodies if the quantities

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{4}$$

and

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2} \tag{5}$$

are introduced as effective measures of elastic stiffness, E^*, and radius of curvature, R^*. Material constants and (local) radius of curvature indexed 1 and 2 refers to the properties pertinent to each individual body. The generalization in Eq. (4) and in Eq. (5) was first suggested in Hertz' original article [1] at elastic (level I) contact but is applicable, within good accuracy, also at evolving plastic deformation (level II and level III), cf. e.g. [4–8]. Naturally, when plasticity is present also the plastic constitutive properties have to be generalized. It was suggested by Storåkers et al. [5] that in case of rigid plasticity, with power law strain hardening described by the relation

$$\sigma = \kappa\varepsilon^{1/m}, \tag{6}$$

where κ and m are material constants and $m \to \infty$ represents ideally plastic behavior, the generalization

$$\frac{1}{\kappa^{*m}} = \frac{1}{\kappa_1^m} + \frac{1}{\kappa_2^m} \tag{7}$$

applies at level III spherical contact problems. It should be noted in passing that a corresponding generalization scheme does not exist for sharp contact problems, as discussed in detail in [9]

When it comes to generalization, or correlation, in the context of σ_{rep}, much knowledge has also been gained. In this case, sharp contact problems are well understood as it has been shown; cf. e.g. Larsson [10,11], that high accuracy correlation can be achieved in a general situation by using two-parameter descriptions of σ_{rep} also accounting for strain-hardening. Regarding the latter feature, in some studies, cf. e.g. [12,13] also the initial yield stress has been used to correlate sharp indentation yielding less accurate results. Basically the same type of investigations has been applied to spherical contact problems, cf. e.g. [5–7,14–16] but the overall characteristics of the problem were not fully understood until Olsson and Larsson [17] presented formulae for a general correlation of global contact properties at, in particular, elastic–plastic (level II) spherical contact problems. In [17], the representative stress was determined at a strain value

$$\varepsilon_{rep} = 0.2a/R, \tag{8}$$

as previously suggested in [5,14,15], and high accuracy results were obtained correlating indentation results and, based on the generalization quantities discussed above, also general spherical contact problems.

With the above mentioned, it is clear that spherical (and sharp) contact problems are nowadays fairly well understood. However, with this understanding follows the insight that there are additional problems that need to be investigated further. One of these problems of substantial practical importance concerns the case of spherical contact between dissimilar materials. This is particular so when level III contact problems are at issue. In such a case the material hardness (average contact pressure) is determined from Eq. (3) and if ideally plastic or low hardening materials are considered then

$\sigma_{rep} = \sigma_y$, (9)

σ_y being the yield stress of the elastic–ideally plastic material. Clearly, if the two materials are dissimilar at particle–particle contact, see Fig. 2, with different yield stress equilibrium is not possible at strictly level III conditions. This matter was implicitly discussed by Martin and Bouvard [18] but only in the context of definition of σ_{rep} and it was suggested that

$$\sigma_{rep} = Min(\sigma_{y1},\ \sigma_{y2}), \tag{10}$$

should be used in this situation. However, no further discussion about the implications for the mechanical behavior was presented. Indeed, to the authors' knowledge, this problem has not been discussed in detail previously in the literature and it is the intention here to remedy this shortcoming.

In doing so, the spherical contact problem depicted in Fig. 2 will be extensively investigated using the finite element method. The investigation is purely a numerical one based on the fact that a full understanding of the mechanics involved is aimed at and it is then of utmost importance to be able to tailor the constitutive behavior of the materials in contact in order to be able to describe different features in an accurate manner also accounting for large deformations. The analysis is founded on classical Mises elastoplasticity assuming, based on the discussion above, ideally plastic behavior. An extension of the results to more general contact

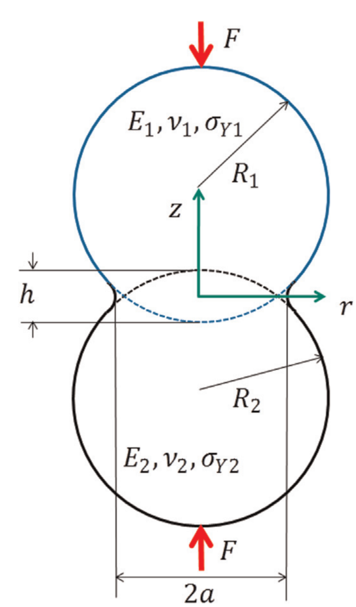

Fig. 2. Schematic of the spherical contact problem.