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Bio-inspired solution for optimal adhesive performance

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Abstract

In recent years there has been a growing interest into high performance bioinspired adhesives. This communication focuses on the adhesive behavior of a rigid cylinder that indents an elastic layer coated on a rigid substrate. With the assumption of short range adhesive interactions (JKR type) the adhesive solution is obtained very easily starting from the adhesiveless one. We show that ultrastrong adhesion (up to theoretical material strength) can be reached in line contact by reducing the thickness of the layer, typically down to the nanoscale size, which suggests a new possible design for "optimal adhesion". Adhesion enhancement occurs as an increase of the actual pull-off force, which is further enhanced by Poisson's ratio effects in the case of nearly incompressible layer. The system studied could be an interesting geometry for an adhesive system, but also a limit case of the more general class of layered systems, or FGMs (Functionally Graded Materials). The model is well suited for analyzing the behavior of polymer layers coated on metallic substrates.

Keywords: Adhesion; layer; JKR model; Adhesion enhancement;

1. Introduction

Adhesion is a very flourishing field in contact mechanics. Even if big steps forward have been undertaken, a lot remains to do. The fundamental solution of an adhesive sphere indenting an halfspace has been discussed long time ago leading to the very known solutions of JKR (Johnson et al., (1971)) and DMT (Derjaguin et al., (1975)), which, after Tabor (1977) paper, have been understood as the limit solutions for very soft (JKR) and very hard (DMT) contacting bodies. The situation for rough contact is instead much less clear and a big effort has been put by many researchers to unveil how rough contact behaves (Pastewka & Robbins (2014), Persson & Scaraggi, (2014), Joe et al. (2018), Ciavarella et al. (2017), Ciavarella & Papangelo (2018a), Ciavarella & Papangelo (2018b)). In the last decade many researchers have developed models and designed surfaces trying to imitate nature adhesive strategies,

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which have been proved to be very effective. The two avenues that have been followed are based on patterned surfaces with dimples (McMeeking et al. (2010), Papangelo & Ciavarella (2017), Papangelo & Ciavarella (2018)) of pillars (Kim et al. (2006), Del Campo et al. (2007), Gorb et al. (2007)). In this note we are studying a possible way to optimize adhesion devices by reducing length scales involved in the geometry (Gao & Yao, 2004). A significant amount of study has been devoted to the case of halfspace geometry, for which the optimal shape for maximum pulloff force is found to be concave, although it is not ”robust” to surface geometry errors (Yao and Gao, 2006). Enhancement of adhesion due to surface geometries is also known in mushroom-shaped fibrils (Peng and Cheng, 2012), rodlike particles (Sundaram and Chandrasekar, 2011), or moving to functionally graded materials (FGMs) which are increasingly used in engineering, and have been also used in nature as a result of evolution (Suresh, 2001, Sherge & Gorb, 2001). Indeed, few authors have explored the behaviour of attachments using FGMs (Chen et al., 2009a, 2009b, Jin et al., 2013), finding interesting results and possible avenues to design ”optimal” adhesive systems.

However, curiously a much simpler geometry (which is in a sense a limit case of FGM) is that of adhesion with a layer on a rigid foundation. In his well known book, Johnson (1985) suggested an elementary formulation to obtain asymptotic results for the contact pressure between a frictionless rigid indenter and a thin elastic layer supported by a rigid foundation. Jaffar (1989) later on used the same technique for the axisymmetric case, and finally Barber (1990) generalized it to the arbitrary, three-dimensional problem for the thin elastic layer.

A typical assumption made is that of the JKR model (Johnson et al., 1971) which corresponds to very short range adhesion where adhesive forces are all within the contact area. Solving the JKR problem is simple generalizing the original JKR energetic derivation assuming calculation of the strain energy in adhesiveless contact, and unloading at constant contact area (see Argatov et al. (2016), Popov et al. (2017), Willert et al. (2016), Ciavarella (2018)). The underlying assumption of (Ciavarella, 2017) is that the contact area distributions are the same as under adhesiveless conditions (for an appropriately increased normal load). There are no approximations involved if the geometry is that of a single line or axisymmetric contact, as the solution is exact within the JKR assumption of infinitely short adhesion range, and states that the indentation δ under adhesive conditions for a given surface energy w is

$$\delta = \delta_1 - \sqrt{2wA'/P_1''} \tag{1}$$

where δ_1 is the adhesiveless indentation, A' is the first derivative of contact area and P_1'' the second derivative of the adhesiveless load with respect to δ_1. Then, the adhesive load is

$$P = P_1 - P_1' \sqrt{2wA'/P_1''} \tag{2}$$

Hence, the asymptotic solutions for the adhesive thin layer problems are found quite simply from the adhesiveless solutions of Johnson (1985), Jaffar (1989) and Barber (1990). In this work we will focus on the two-dimensional Hertzian problem, while the three dimensional case has been addressed in a previous work (Papangelo (2018). We shall then discuss implications, and suggest potential strategies for ”optimal” adhesive performance.

2. The model

2.1. Frictionless foundation

Following Johnson (1985), we assume that plane sections within the layer remain plane upon indentation, so that the in-plane displacements of the layer with components u_1, u_2 are independent of z (see Fig. 1). We transform the adhesionless solution into an adhesive one with no further approximation following (Ciavarella (2017)) and thus we

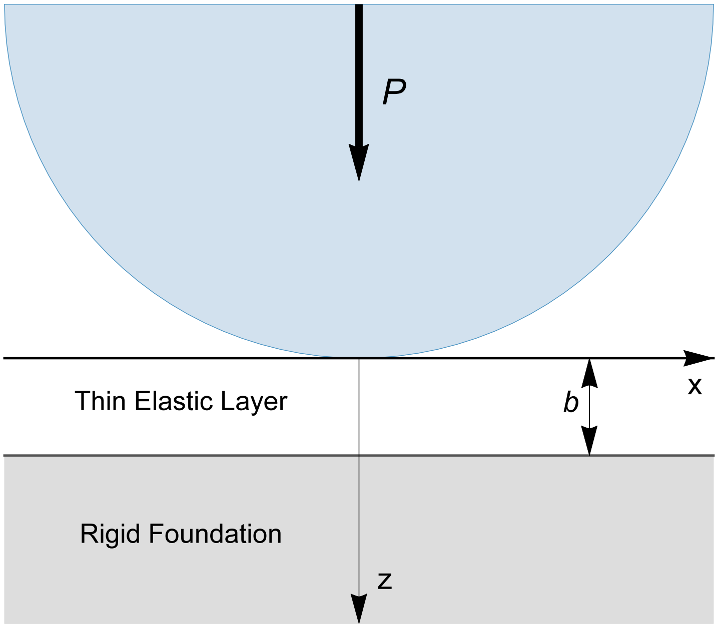

Fig. 1. The geometry for a rigid cylinder indenting a layer supported by a rigid foundation

simply retrieve the JKR adhesive solution applying (1, 2) in the case of a single line contact[1], hence the only hypothesis we made is the ”thin layer”, which we will check in the last section of this communication.

Let us consider (see Fig.1) a layer indented by a frictionless rigid cylinder of radius R, and assume the thickness of the layer b is small compared with the half-width of the contact size a, i.e. $b << a$, (thin layer assumption).

The adhesiveless solution gives for indentation δ_1 and load P_1 (Johnson, (1985))

$$\delta_1 = a^2/2R \tag{3}$$

$$P_1 = \frac{2}{3}\frac{E^* L}{Rb}a^3 = \frac{2^{5/2}}{3}\frac{E^* L R^{1/2}}{b}\delta_1^{3/2} \tag{4}$$

being E^* the plane strain elastic modulus, L the contact length, a the contact semi-width. For a given contact area $A = 2aL$, the adhesive solution is obtained with obvious algebra using (2)

$$P = \frac{4}{3}\frac{E^* L\sqrt{2R\delta_1}}{b}\left(\delta_1 - 3\sqrt{\frac{b}{2E^*}w}\right) \tag{5}$$

in terms of the adhesionless indentation δ_1. To find the minimum load (pull-off), the condition $P' = 0$ gives

$$\delta_{1,PO} = \sqrt{\frac{b}{2E^*}w} \quad ; \quad a_{PO} = \sqrt{2R}\left(\frac{b}{2E^*}w\right)^{1/4} \tag{6}$$

[1] With the same procedure also axisymmetric contacts can be solved exactly.

(where notice that we have to assume $a_{PO} >> b$ to be consistent with the thin layer assumption), and hence substituting into (5)

$$P_{PO} = -\frac{8}{3}\frac{E^* L R^{1/2}}{(2b)^{1/4}}\left(\frac{w}{E^*}\right)^{3/4} \tag{7}$$

whereas the average stress in the contact at pull-off is

$$\sigma_{PO} = \frac{P_{PO}}{A_{PO}} = -\frac{2}{3}\sqrt{2}\left(\frac{E^* w}{b}\right)^{1/2} = -\frac{2}{3}\sqrt{2}\frac{K_{Ic}}{\sqrt{b}} \tag{8}$$

where K_{Ic} is toughness of the contact. Hence, notice that the JKR solution simply gives the Griffith condition imposed by a Stress Intensity Factor which scales only with the size the layer b and not any other length scale (like the radius of the punch). The interesting result is that as $b \to 0$ the limit of the force also goes to ∞. Eq. (8) can be written in dimensionless form as

$$\frac{\sigma_{PO}}{\sigma_{th}} = -\frac{2}{3}\sqrt{2}\left(\frac{E^*}{\sigma_{th}}\right)\widetilde{l}_a^{1/2} \tag{9}$$

where $\widetilde{l}_a = \frac{w/E^*}{b}$ is a dimensionless adhesion parameter. Figure 2 shows how increasing $\widetilde{l}_a$ (for a given set of material constants this implies a reduction in the layer thickness b) the average pull-off stress is increased.

Since σ_{PO} will be bounded by theoretical strength, the situation is analogous to the well known case of a fibrillar structure in contact with a rigid halfspace, like that discussed for Gecko and many insects who have adopted nanoscale fibrillar structures on their feet as adhesion devices (Gao & Yao, 2004). In our case, to have a design insensitive to small variations in the tip shape, we would simply need to go down in the scale of the layer thickness. In fact, imposing $\sigma_{PO}/\sigma_{th} = -1$, we obtain a critical value for $\widetilde{l}_a$, namely $\widetilde{l}_{a,cr}$, above which the theoretical strength of the material is reached, which also defines, for fixed material properties, the order of magnitude of the "critical" thickness of the layer below which we expect theoretical strength

$$\widetilde{l}_{a,cr} = \frac{9}{8}\left(\frac{\sigma_{th}}{E^*}\right)^2 \to b_{cr} = \frac{8}{9}\frac{E^* w}{\sigma_{th}^2} \tag{10}$$

Taking $w = 10$ mJ/m^2, $\sigma_{th} = 20$ MPa and $E^* = 1$ GPa, like done in (Gao & Yao, 2004), we estimate $\widetilde{l}_{a,cr} = 4.5 \times 10^{-3}$ or $b_{cr} = \frac{8}{9}\frac{10^9 10^{-2}}{(20\times10^6)^2} = 22$ nm, which is of the same lengthscale of the estimate (of a different geometry) of 64 nm robust design diameter of the fiber of the fibrillar structure. Hence, with this size of layer of nanoscopic scale, we would be able to devise a quite strong attachment for any indenter.

In the halfplane limit case, from Barquins (1988), Chaudhury et al. (1996) we have for the cylinder

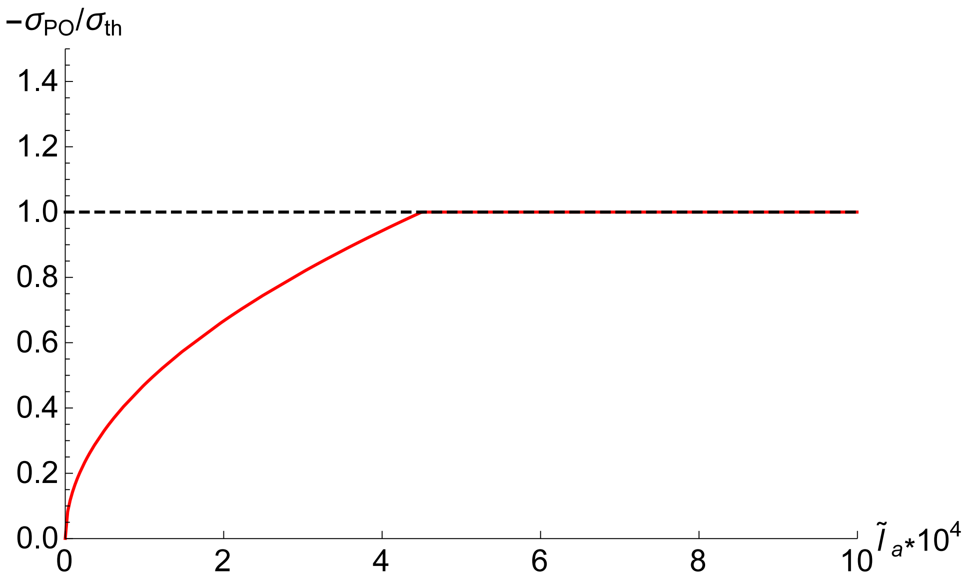

Fig. 2. Dimensionless pull-off stress versus the dimensionless adhesion parameter $\widetilde{l}_a$. The average pull-off stress is bounded at $-\frac{\sigma_{PO}}{\sigma_{th}} = 1$.

$$P_{PO,HP} = -3L\left(\frac{\pi E^* w^2 R}{16}\right)^{1/3} \quad ; \quad a_{PO,HP} = \left(\frac{2wR^2}{\pi E^*}\right)^{1/3} \tag{11}$$

$$\sigma_{PO,HP} = \frac{P_{PO,HP}}{A_{PO,HP}} = \frac{-3}{2}\left(\frac{\pi^2 E^{*2} w}{32R}\right)^{1/3} \tag{12}$$

which does include some dependence on elastic modulus which is not present in the axisymmetric halfspace problem of JKR model (Johnson et al., 1971), but it seems to be quite different in terms of power law dependence from the ”layered” case. Indeed, take the ratio

$$\frac{P_{PO}}{P_{PO,HP}} = \frac{8}{9}\frac{16^{1/3}}{\pi^{1/3}2^{1/4}}\frac{R^{1/6}}{b^{1/4}}\left(\frac{w}{E^*}\right)^{1/12} \tag{13}$$

which shows how there are really different power law dependences in the layer limit.

The full curve $P-\delta$ is then obtained using (1)

$$\delta = a^2/2R - \sqrt{2w\frac{b}{E^*}} \tag{14}$$

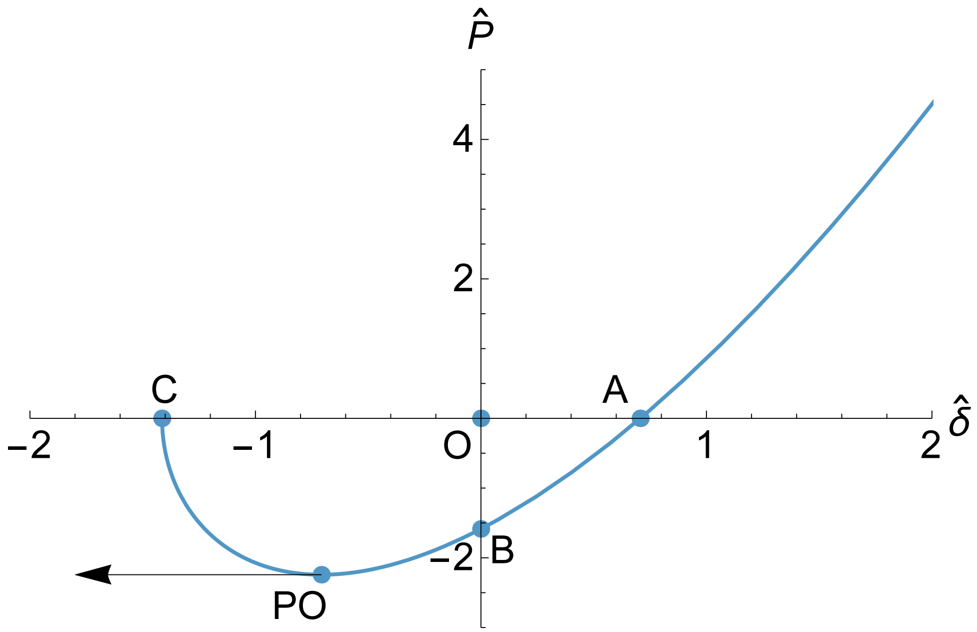

Fig. 3. Dimensionless load vs indentation curve for a rigid cylinder indenting a layer on a frictionless rigid foundation.

so extracting the equation for the contact area, using $\delta_1 = a^2/2R$, and then substituting back in the solution (5), we get

$$\widehat{P} = \frac{4}{3}\sqrt{2}\left(\widehat{\delta} + \sqrt{2}\right)^{1/2}\left(\widehat{\delta} - \frac{1}{\sqrt{2}}\right) \tag{15}$$

where we have defined dimensionless quantities

$$\widehat{\delta} = \frac{\delta}{\sqrt{w\frac{b}{E^*}}} \quad ; \quad \widehat{P} = \frac{P}{\frac{E^* L R^{1/2}}{b^{1/4}}\left(\frac{w}{E^*}\right)^{3/4}} \tag{16}$$

so that $\widehat{P}_{PO} = -\frac{8}{3\times 2^{1/4}} = 2.2424$ and $\widehat{\delta}_{PO} = -\frac{\sqrt{2}}{2} = 0.707$.

Following Fig. 3, the solution is plotted in dimensionless terms. Starting from remote locations, one finds contact only when there is contact with the undeformed surfaces (JKR makes it not possible to model long range adhesion) and hence until point O (the origin of the coordinate system) is reached. Then under force control, one would obtain a jump to point B where force remains zero but one finds an effective indentation $\widehat{\delta}_B$. From this point on, one could load in compression and go up in the figure, or start unloading that ends at the pull-off point ”PO”, with coordinates $\left(\widehat{\delta}_{PO}, \widehat{P}_{PO}\right)$. Alternatively, if we were under displacement control, at the point of first contact we would build up adhesive force and jump to point ”A”. Unloading the indenter would proceed along the loading curve until the adhesive force is reduced back to zero in point ”C”. Hence, there is no pull-off under displacement control, contrary to the classical JKR case.

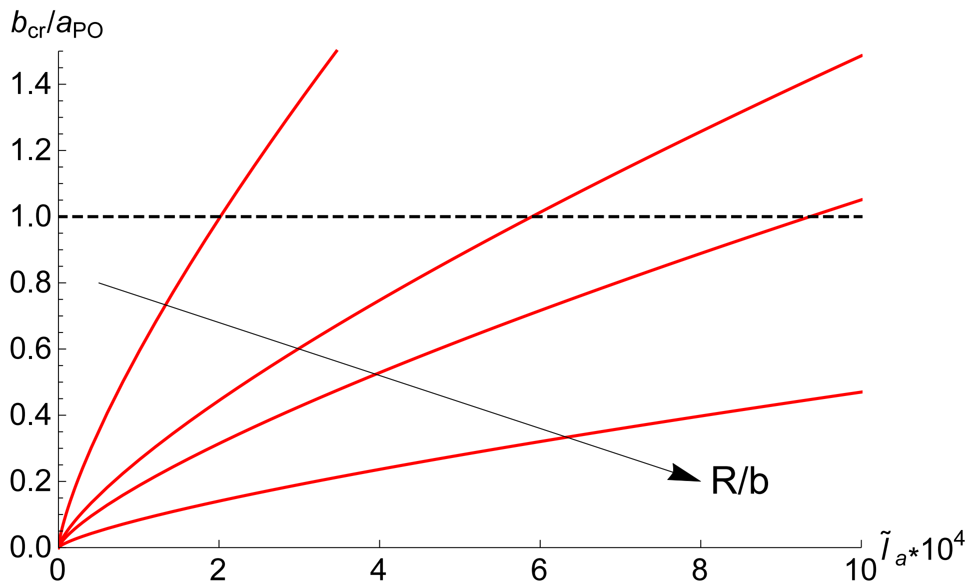

Fig. 4. The ratio $\frac{b_{cr}}{a_{PO}}$ is plotted versus $\widetilde{l_a}$ for $w = 10$ mJ/m^2, $\sigma_{th} = 20$ MPa and $E^* = 1$ GPa and $R/b = [10, 50, 100, 500]$. The present analysis is valid for $b_{cr}/a_{PO} \ll 1$.

To ascertain the range of validity of the present analysis we finally check the thin layer assumption, which requires the thickness of the layer to be smaller than the contact semi-width. Using the same material properties introduced above, we estimate the ratio b_{cr}/a_{PO} as

$$\frac{b_{cr}}{a_{PO}} = \frac{8}{9 \times 2^{1/4}} \frac{\widetilde{l}_a^{3/4}}{\sqrt{R/b}\,(\sigma_{th}/E^*)^2} \tag{17}$$

Eq. (17) is plotted in Fig. 4, for $R/b = [10, 50, 100, 500]$ and shows that the proposed design strategy is effective, in particular for indenters with characteristic dimension "R" much larger that the layer thickness. For example a micrometric pillar indenting a nanometric layer would experience high adhesive performance fulfilling the thin layer assumption.

2.2. Bonded layer

Repeating the arguments presented above for a bonded compressible layer (Johnson (1985)), one finds

$$P_{PO} = -\frac{8}{3} \frac{E^* L R^{1/2}}{(2b)^{1/4}} \frac{(1-\nu)^{1/2}}{2^{1/4}(1-2\nu)^{1/4}} \left(\frac{w}{E^*}\right)^{3/4} \tag{18}$$

$$a_{PO} = \sqrt{2R}\left(\frac{(1-2\nu)}{(1-\nu)^2} \frac{b}{E^*} w\right)^{1/4} \tag{19}$$

and therefore for the bonded layer the Poisson's effect appears, which only changes a prefactor in the result for the frictionless foundation — but notice this prefactor makes the load diverge towards the incompressible limit $\nu = 0.5$. Hence, in this case the average stress in the contact at pull-off is

$$\sigma_{PO} = \frac{P_{PO}}{A_{PO}} = -\frac{4}{3}\frac{(E^*w)^{1/2}}{b^{1/2}}\frac{1-\nu}{2\,(1-2\nu)^{1/2}} \tag{20}$$

and hence here by equating σ_{PO} to theoretical strength, we obtain

$$b_{cr} = \left[\frac{1}{2}\frac{(1-\nu)^2}{1-2\nu}\right]\frac{8}{9}\frac{E^*w}{\sigma_{th}^2} = \left[\frac{1}{2}\frac{(1-\nu)^2}{1-2\nu}\right]b_{cr,frictionless} \tag{21}$$

and therefore this time the critical layer thickness becomes dependent on Poisson's ratio, rendering the layer adhesive *much more effective*.

2.3. Incompressible bonded layer

The results of the previous paragraph hold until the layer is nearly incompressible, in which case a similar procedure yields

$$P_{PO} = -\frac{8}{5}L\frac{(3Rw)^{2/3}}{(2b)^{1/2}}w^{1/6}E^{*1/6} \tag{22}$$

and $\delta_{1,PO} = b\left(\frac{w}{3E^*R}\right)^{1/3}$ while $a_{PO} = \sqrt{6Rb\left(\frac{w}{3E^*R}\right)^{1/3}}$, which is therefore rather different from the frictionless counterpart. Hence, in this case the average stress in the contact at pull-off is

$$\sigma_{PO} = \frac{P_{PO}}{A_{PO}} = -\frac{2}{5}\frac{(3Rw^2E^*)^{1/3}}{b} \tag{23}$$

and we return to see effects of the radius of the indenter (i.e. qualitative effects on the geometry) like in the halfplane problem.

3. Conclusions

In this communication, we show that ultrastrong adhesion can be reached in line contact for contact of a Hertzian indenter with ultrathin layers supported by a rigid foundation, suggesting a new possible strategy for "optimal adhesion". There are some details which differ in plane contact vs axisymmetric contact (see Papangelo (2018)): indeed, in line contact adhesion enhancement occurs as an increase of the actual pull-off force, while in the Hertzian axisymmetric case pull-off differs form the classical JKR halfspace solution only by a prefactor. However, in both cases the enhancement occurs because the dominant length scale for the stress intensity factor at the contact edge is the layer thickness, and this induces a reduction of the size of contact needed to sustain the pull-off force. These effects are remarkably further enhanced by Poisson's ratio effects in the case of nearly incompressible layer.

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