



Biomimetic study of rolling transport through smooth muscle contraction

Lei Chen ^a, Shaohua Chen ^{a,*}, Huajian Gao ^{b,**}

^a LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

^b School of Engineering, Brown University, Providence, RI 02912, USA



ARTICLE INFO

Article history:

Received 16 June 2014

Received in revised form 7 August 2014

Accepted 13 August 2014

Available online 1 September 2014

Keywords:

Biomimetic experiment

Rolling adhesive contact

Rolling transport

Strain gradient

Energy release rates

ABSTRACT

Inspired by the rolling behavior of oosperm through smooth muscle contraction of fallopian tube, a simple biomimetic experiment is devised in order to disclose the possibly mechanical transport mechanism. An interesting experimental observation demonstrates that an elastic strain gradient can be utilized to transport a soft latex bubble on a stretchable substrate by rolling. A corresponding theoretical model is established, in which an elastically three-dimensional bubble contacts adhesively on an elastic substrate subject to strain gradient. The initiation and steady-state energy release rates for such a rolling motion are achieved and analyzed. The influencing factors of rolling are found. The finding may have general implications on designing active transport systems with strain gradient.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Biological transport via tissue contraction is a ubiquitous phenomenon in living systems. A prominent example is the transport of oosperm from ovary to uterus through the fallopian tube during pregnancy. While it is clear that the transport of oosperm involves smooth muscle contraction [1,2], the detailed mechanism still remains elusive [1–7], due in part to the complexity of cell-substrate interactions via receptor-ligand binding as well as various physical forces inside and outside of the cytoskeleton [8–12]. Cells are known to respond to mechanical forces exerted through surrounding fluid, adhering beads or substrates [9,12–14], and they could detach, slip or roll on a substrate in response to these forces [15–22]. For example, cells on a cyclically stretched substrate tend to reorient themselves away from the stretching direction [23–27], and cells migrate along a substrate with rigidity gradient (durotaxis) [18]. Blood cells are found to undergo a transition from rolling to translational motion on a blood vessel wall under increasing hydrodynamic shear forces [19], exemplifying a general fact that it takes less effort for a round object to roll than to slip on a substrate [28,29].

Could muscle contraction actually provide a driving force for the transport of an object? If so, what determines the direction of transport? While a symmetric contraction cannot provide a direction of motion, a strain gradient generated by a spatially non-uniform contraction could. Here we examine the hypothesis that an elastic strain gradient along a non-uniformly deforming substrate could induce the rolling of a particle in the direction of strain gradient.

In this paper, a biomimetic experiment is conducted first in order to verify our hypothesis. Then, a corresponding contact model of an elastic bubble adhering on an elastic substrate subject to strain gradient is established, in which influencing factors of the initial and steady-state rolling are analyzed. Conclusions are made finally.

2. Biomimetic experiment of adhesive rolling

To demonstrate the basic phenomenon, we devised a simple experiment in which a soft elastic latex bubble is placed in adhesive contact with a sticky and non-uniformly deforming substrate. In the experimental set-up shown in Fig. 1(a), a sticky elastic layer made of thermal plastic rubber is put on a rigid epoxy resin substrate. To create a strain gradient on the surface of the elastic layer, an interfacial crack is introduced near the edge of the interface and a horizontal displacement is imposed at the detached end of the elastic layer. As the layer is stretched beyond a critical strain, the interfacial crack starts to propagate, inducing an elastic strain gradient in the layer that moves with the crack tip.

* Corresponding author. Tel.: +86 10 82543960.

** Corresponding author.

E-mail addresses: chenshaohua72@hotmail.com (S. Chen), huajian_gao@brown.edu (H. Gao).

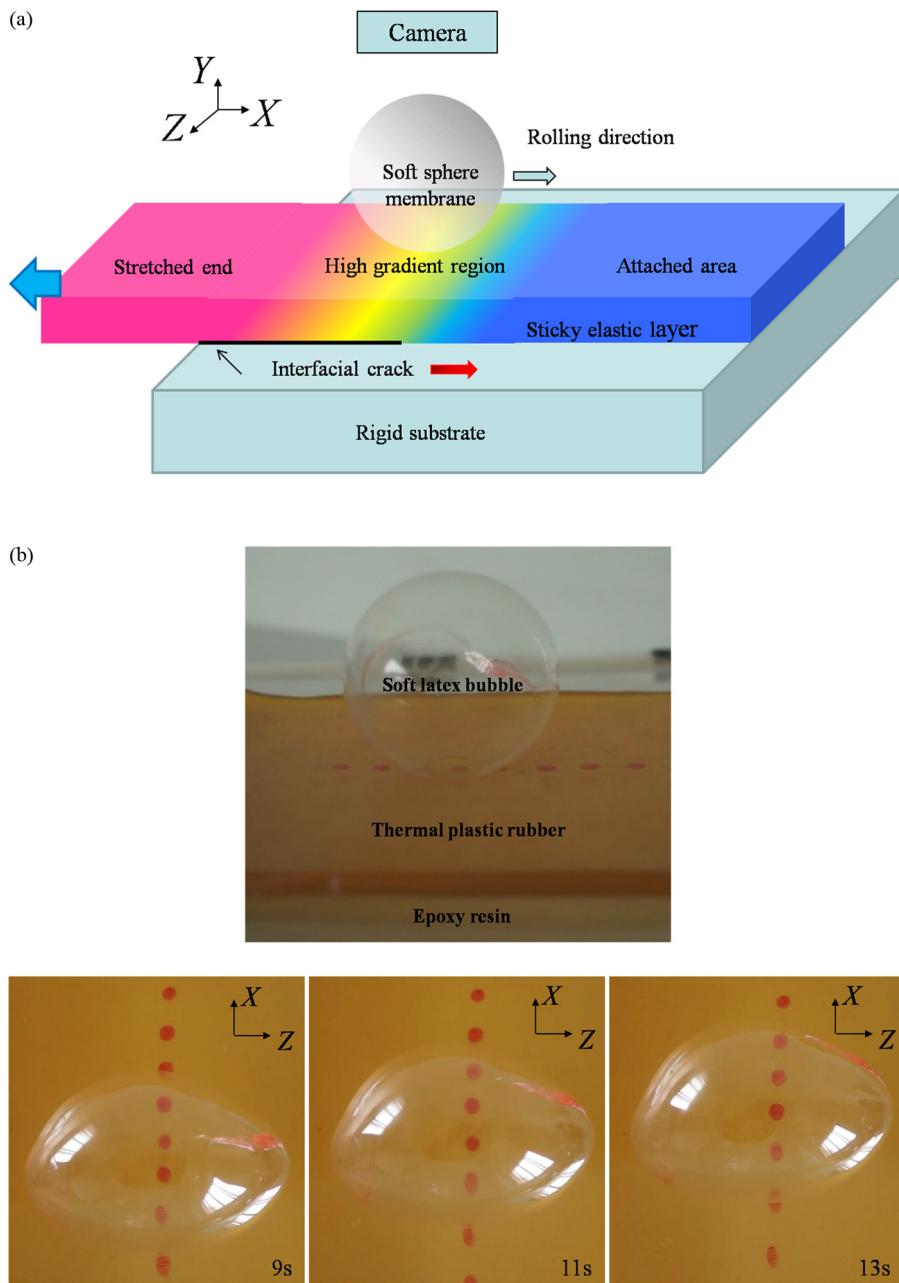


Fig. 1. The experimental set-up. (a) Schematic of a soft latex bubble placed on the surface of a sticky thermal plastic rubber layer adhering to a relative rigid epoxy resin substrate. A sharp strain gradient is created near the tip region of an interfacial crack between the rubber layer and rigid substrate, which moves the bubble along the surface through rolling; (b) The soft bubble on the stretched strip moves in the propagating direction of the interface crack.

The latex bubble is then placed on the surface of the elastic layer ahead of the interfacial crack tip, where the layer is well bonded to the rigid epoxy resin substrate. As the elastic layer is stretched but before the crack tip reaches the bubble, the surface strain is nearly zero due to the constraint from the rigid substrate. As the moving crack tip reaches where the bubble adheres and brings with it an elastic strain gradient across the crack tip, the elastic bubble begins to roll along the surface, as shown in Fig. 1(b).

It is easy to show that the observed bubble motion is not caused by gravity by simply repeating the experiment with the whole device tilted at a small angle while observing the bubble to continue to roll along the strain gradient against gravity, as shown in Fig. S1 in the Supplementary Material.

Supplementary Fig. S1 related to this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.colsurfb.2014.08.014>.

If the propagating velocity of the interface crack is increased, the bubble is observed to roll faster with the crack tip. If the interface crack is stopped, the bubble stops too at a small distance ahead of the crack tip. When the interface crack propagates slowly, the bubble rolls with nearly the same velocity as that of the crack tip. The phenomenon is somewhat analogous to a boat traveling with a moving tide. If the bubble is initially placed far away from the interface crack, rolling does not occur until the crack tip moves near the bubble. If the bubble is placed behind the interface crack tip, it hardly moves at all as the crack propagates away. Only when the bubble lies within the strain gradient region near the tip of a moving interface crack does it roll along with the crack. No external force is applied on the bubble during the experiment.

Previous researches have shown, both theoretically and experimentally, that a uniform elastic strain imposed on a substrate tends

to reduce the contact area of a particle adhering on a substrate [30–36]. In the present experiment, the strain field in the elastic layer is highly non-uniform across the tip of the interface crack. Since the elastic strain tends to reduce the contact area between the particle and substrate, one may assume that there will be a driving force for the particle to move along the strain gradient in order to minimize the local strain in the neighborhood of the particle. A comparable finding to the present rolling motion induced by the inhomogeneous strain field is the spontaneous migration of droplets resulted from an asymmetrical chemical interaction [37–41]. Furthermore, it was found recently that temperature gradient could also be a driving force for a bubble to move against liquid flow [42]. All the interesting phenomena indicate that the heterogeneity of environmental fields can be a generally driving force for transport.

3. Theoretical model and analysis

To model the experiment, we developed a theoretical model with a pressurized gas-filled spherical bubble adhering on an elastic substrate subject to a strain gradient.

For such a gas-filled balloon in adhesive contact with an initially stress-free substrate via van der Waals interaction, the contact area is a circle of radius [43]

$$a = \sqrt{\frac{4\Delta\gamma R}{\Delta P_i(1 - 16\lambda)}} \left[2 + \frac{3RP_i(1 - \nu)}{E_m h_m} \right]^{-(1/2)} \quad (1)$$

where R is the bubble radius; E_m , ν and h_m are the Young's modulus, Poisson's ratio and thickness of the membrane, respectively; $\Delta P_i = P_i - P_0$ is the overpressure in the bubble, P_i being the internal pressure and P_0 the external (atmospheric) pressure; and λ is a constant related to the material constants of the system [43]. It should be noted that even for a liquid-filled balloon, rolling motion should also be found experimentally and a similar model can be established, of which the initial contact area between the liquid-filled balloon and the initially stress-free substrate has been given in [44]. In this paper, we only consider the gas-filled case.

3.1. The initiation of rolling

Initially, the adhering bubble has a membrane strain ε_0 and the substrate is stress-free. Now introduce a strain gradient $\varepsilon_s(x) = \varepsilon_1 - \eta x$ in the x -direction in the substrate, where $\eta = (\varepsilon_1 - \varepsilon_2)/2a$, ε_1 and ε_2 being strains at the trailing and leading edges of the contact region, as shown in Fig. 2. Due to the substrate strain, the x -component of the membrane strain in the contact region becomes $\varepsilon_m^{\text{init}}(x, z) = \varepsilon_0 + \varepsilon_1 - \eta x$.

To determine the initiation driving force for bubble motion, consider an infinitesimal virtual displacement δx in the x -axis direction of the contact region as a result of rolling. As shown in Fig. 2, the rolling process involves the detachment of a small area $\delta A_t \approx 2a\delta x$ near the trailing edge (left shadow area) and attachment of an area δA_l (right shadow area) near the leading edge.

At the trailing edge, the additional strain in the membrane above ε_0 induced by the substrate strain will be released due to the detachment. The released strain energy at the trailing edge can be obtained as follows

$$\begin{aligned} \delta U_{\text{init}}^t &= \frac{1}{2} E_m h_m \int_{\delta A_t} [\varepsilon_m^{\text{init}}(x, z)]^2 dA - \frac{1}{2} E_m h_m \int_{\delta A_t} (\varepsilon_0)^2 dA \\ &= \frac{1}{2} E_m h_m a \cdot \delta x \left[2\bar{\varepsilon}(\bar{\varepsilon} + 2\varepsilon_0) + \pi(\bar{\varepsilon} + \varepsilon_0)a\eta + \frac{4a^2\eta^2}{3} \right] \end{aligned} \quad (2)$$

where $\bar{\varepsilon} = (\varepsilon_1 + \varepsilon_2)/2$ is the average strain in the contact area.

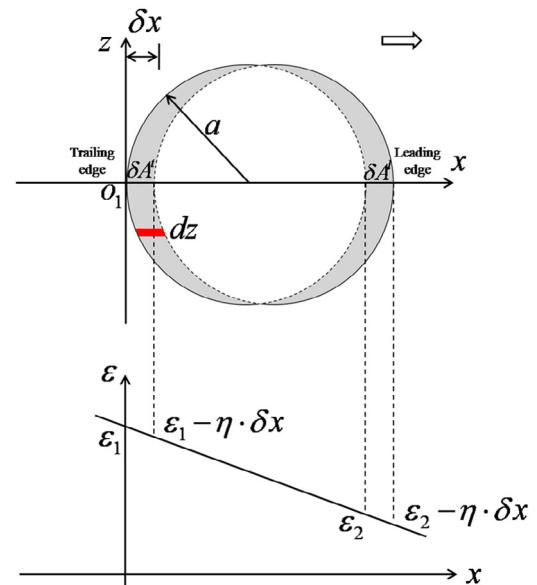


Fig. 2. The theoretical model of the contact region of a spherical bubble rolling on a substrate with an elastic strain gradient; a denotes the radius of contact region and δx a small displacement of the bubble in the x -axis direction.

Then, the energy release rate at the trailing edge can be obtained,

$$G_{\text{init}}^t = \lim_{\delta x \rightarrow 0} \frac{\delta U_{\text{init}}^t}{\delta A_t} = \frac{1}{4} E_m h_m \left[2\bar{\varepsilon}(\bar{\varepsilon} + 2\varepsilon_0) + \pi(\bar{\varepsilon} + \varepsilon_0)a\eta + \frac{4a^2\eta^2}{3} \right] \quad (3)$$

It is worth noting that there is no energy change at the leading edge as the membrane attaches to the substrate, i.e.

$$G_{\text{init}}^l = 0 \quad (4)$$

The total energy release rate is

$$G_{\text{init}} = G_{\text{init}}^t - G_{\text{init}}^l = \frac{1}{4} E_m h_m \left[2\bar{\varepsilon}(\bar{\varepsilon} + 2\varepsilon_0) + \pi(\bar{\varepsilon} + \varepsilon_0)a\eta + \frac{4a^2\eta^2}{3} \right] \quad (5)$$

The criterion for the initiation of rolling is then

$$G_{\text{init}} \geq \Delta\Gamma, \quad \Delta\Gamma = \Delta\gamma_{\text{trailing}} - \Delta\gamma_{\text{leading}} \quad (6)$$

where $\Delta\gamma_{\text{trailing}}$ and $\Delta\gamma_{\text{leading}}$ represent the work of adhesion at the trailing and leading contact edges, which can be determined from the so-called “over-loading” and “under-loading” experiments [45]. Normally, $\Delta\gamma_{\text{trailing}}$ and $\Delta\gamma_{\text{leading}}$ are different due to viscoelastic behaviors at the contact interface. This result indicates that both the strain gradient and the average strain influence the initiation of motion.

3.2. The steady state rolling

In our experiment, a gradient strain field moves along with the crack tip and toward the adhering latex bubble. Once Eq. (6) is satisfied, the bubble starts to roll. Subsequently, the membrane of the bubble continuously attaches to the substrate at the leading edge and detaches at the trailing edge. Within the contact region, the membrane strain can be expressed as

$$\varepsilon_m^{\text{ss}}(x, z) = \varepsilon_0 + \eta(a - x + \sqrt{a^2 - z^2}) \quad \text{for } (a - x)^2 + z^2 \leq a^2 \quad (7)$$

which is equal to ε_0 at the leading edge $x = a + \sqrt{a^2 - z^2}$ where the membrane is attached to the substrate and increases with the substrate strain until detachment occurs at the trailing edge $x = a - \sqrt{a^2 - z^2}$.

During the steady state rolling, the released energy at the trailing edge, similar to the calculation in Eq. (2), can be achieved,

$$\delta U_{ss}^t = \frac{1}{2} E_m h_m \int_{\delta A_t} [\varepsilon_m^{ss}(x, z)]^2 dA - \frac{1}{2} E_m h_m \int_{\delta A_t} (\varepsilon_0)^2 dA \\ = \frac{8}{3} E_m h_m \eta^2 a^3 \cdot \delta x + \pi E_m h_m \varepsilon^0 \eta a^2 \cdot \delta x \quad (8)$$

At the leading edge, no energy change happens, which is similar to the case of the initiation of rolling.

Then, the global energy release rate is

$$G_{ss} = \lim_{\delta x \rightarrow 0} \frac{\delta U_{ss}^t}{\delta A_t} = E_m h_m \alpha \eta \left(\frac{4}{3} a \eta + \frac{\pi}{2} \varepsilon_0 \right) \quad (9)$$

Note that, while G_{init} depends on both the average strain $\bar{\varepsilon}$ and strain gradient η , G_{ss} only depends on η . Therefore, in the absence of a strain gradient, there can be membrane detachment [30–36] but no subsequent directional motion. The average strain in the substrate can only affect G_{init} , hence the initiation of a detachment, but it has no effect on the steady state energy release rate G_{ss} which is necessary for the observed directional motion. It is also interesting to note that G_{init} and G_{ss} also depend on the contact radius a and the inherent membrane strain ε_0 of the bubble.

Comparison between our theoretical prediction and experimental measurement is not conducted so far due to the required material constants and inner pressure in the spherical bubble. Future work will focus on this issue.

4. Conclusion

In summary, we have shown through both experiment and theory that an elastic strain gradient could be utilized to transport particles along a substrate. A bubble contact model has been used to derive the initiation and steady state energy release rates associated with such strain gradient induced motion. This phenomenon could provide a basis for further investigations of a range of biological transport processes by muscle contractions.

Acknowledgments

Support from the National Natural Science Foundation of China (Grant Nos. 11372317, 11125211), the 973 Nano-project (2012CB937500), and the CAS/SAFEA International Partnership

Program for Creative Research Teams are gratefully acknowledged. The work of HG has been supported by the Center for Mechanics and Materials at Tsinghua University.

References

- [1] S.A. Halbert, D.R. Becker, S.E. Szal, *Biol. Reprod.* 40 (1989) 1131–1136.
- [2] R.A. Lyons, E. Saridogan, O. Djahanbakhch, *Hum. Reprod. Update* 12 (2006) 363–372.
- [3] F. Arbab, J. Goldsby, N. Matijevic-Aleksic, G.X. Huang, K.H. Ruan, J.C. Huang, *Hum. Reprod.* 17 (2002) 3053–3059.
- [4] S. Kolle, S. Reese, W. Kummer, *Theriogenology* 73 (2010) 786–795.
- [5] S.P. Martinez, M. Viggiano, A.M. Franchi, M.B. Herrero, M.E. Ortiz, M.F. Gimeno, M. Villalon, *J. Reprod. Fertil.* 118 (2000) 111–117.
- [6] J.T. Norwood, C.E. Hein, S.A. Halbert, R.G.W. Anderson, *Proc. Natl. Acad. Sci. U. S. A.* 75 (1978) 4413–4416.
- [7] J.L.V. Shaw, S.K. Dey, H.O.D. Critchley, A.W. Horne, *Hum. Reprod. Update* 16 (2010) 432–444.
- [8] M. Chrzanowska-Wodnicka, K. Burridge, *J. Cell Biol.* 133 (1996) 1403–1415.
- [9] D.E. Ingber, *J. Cell. Sci.* 104 (1993) 613–627.
- [10] S. Miyamoto, S.K. Akiyama, K.M. Yamada, *Science* 267 (1995) 883–885.
- [11] S.P. Palecek, *Nature* 388 (1997), 210–210.
- [12] N. Wang, J.P. Butler, D.E. Ingber, *Science* 260 (1993) 1124–1127.
- [13] D. Choquet, D.P. Felsenfeld, M.P. Sheetz, *Cell* 88 (1997) 39–48.
- [14] P.R. Girard, R.M. Neren, *J. Cell. Physiol.* 163 (1995) 179–193.
- [15] W.S. Haston, J.M. Shields, P.C. Wilkinson, *Exp. Cell Res.* 146 (1983) 117–126.
- [16] C.G. Balbraith, M.P. Sheetz, *Curr. Opin. Cell Biol.* 10 (1998) 566–571.
- [17] S. Huang, D.E. Ingber, *Nat. Cell Biol.* 1 (1999) E131–E138.
- [18] C.M. Lo, H.B. Wang, M. Dembo, Y.L. Wang, *Biophys. J.* 79 (2000) 144–152.
- [19] B. Lorz, R. Simson, J. Nardi, E. Sackmann, *Europhys. Lett.* 51 (2000) 468–474.
- [20] B. Geiger, A. Bershadsky, *Cell* 110 (2002) 139–142.
- [21] I.B. Bischofs, U.S. Schwarz, *Proc. Natl. Acad. Sci. U. S. A.* 100 (2003) 9274–9279.
- [22] J.Y. Wong, A. Velasco, P. Rajagopalan, Q. Pham, *Langmuir* 19 (2003) 1908–1913.
- [23] V.P. Shirinsky, A.S. Antonov, K.G. Birukov, A.V. Sobolevsky, Y.A. Romanov, N.V. Kabaeva, G.N. Antonova, V.N. Smirnov, *J. Cell Biol.* 109 (1989) 331–339.
- [24] H.C. Wang, W. Ip, R. Boissy, E.S. Grood, *J. Biomech.* 28 (1995), 1543.
- [25] R. Kemkemer, H. Gruler, *Eur. J. Cell Biol.* 74 (1997) 40.
- [26] M. Moretti, A. Prina-Mello, A.J. Reid, V. Barron, P.J. Prendergast, *J. Mater. Sci. Mater. Med.* 15 (2004) 1159–1164.
- [27] S. Jungbauer, H.J. Gao, J.P. Spatz, R. Kemkemer, *Biophys. J.* 95 (2008) 3470–3478.
- [28] W. Ding, A.J. Howard, M.D.M. Peri, C. Cetinkaya, *Philos. Mag.* 87 (2007) 5685–5696.
- [29] W.Q. Ding, H. Zhang, C. Cetinkaya, *Intersoc Conf. Thermal T*, 2008, pp. 920–924.
- [30] S. Chen, H. Gao, *J. Mech. Phys. Solids* 54 (2006) 1548–1567.
- [31] S.H. Chen, H.J. Gao, *Proc. R. Soc.: A Math. Phys.* 462 (2006) 211–228.
- [32] S.H. Chen, H.J. Gao, *Int. J. Mater. Res.* 97 (2006) 584–593.
- [33] S.H. Chen, H.J. Gao, *Int. J. Solids Struct.* 44 (2007) 1939–1948.
- [34] S.H. Chen, H.J. Gao, *J. Mech. Phys. Solids* 55 (2007) 1001–1015.
- [35] J.F. Waters, J. Kalow, H.J. Gao, P.R. Guduru, *J. Adhes.* 88 (2012) 134–144.
- [36] F. Jin, X. Guo, *Int. J. Solids Struct.* 49 (2012) 2349–2357.
- [37] C.D. Bain, G.D. Burnettsall, R.R. Montgomerie, *Nature* 372 (1994) 414–415.
- [38] F. Brochardwyart, P.G. deGennes, *Cr. Acad. Sci. II. B* 321 (1995) 285–288.
- [39] D.F. Dossantos, T. Ondarcuhu, *Phys. Rev. Lett.* 75 (1995) 2972–2975.
- [40] M.E.R. Shanahan, *J. Phys. D Appl. Phys.* 23 (1990) 321–327.
- [41] M.E.R. Shanahan, P.G. deGennes, *Cr. Acad. Sci. II. B* 324 (1997) 261–268.
- [42] M.E.R. Shanahan, K. Seifane, *Sci. Rep. UK* 4 (2014).
- [43] M.E.R. Shanahan, *J. Adhes.* 63 (1997) 15–29.
- [44] M.E.R. Shanahan, *J. Adhes.* 79 (2003) 881–891.
- [45] A.D. Roberts, A.G. Thomas, *Wear* 33 (1975) 45–64.