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# Simulations of sliding adhesive contact between microgear teeth in silicon-based MEMS work in a vacuum environment

*** Nabeel Almuramady[1, 2], Feodor M. Borodich[1]**

[1]School of Engineering, Cardiff University, Cardiff, Wales, UK, CF24 3AA
[2]College of Engineering, Al-Qadisiyah University, Al-Qadisiyah, Iraq

*AlmuramadyNS@cardiff.ac.uk

## ABSTRACT

Sliding friction and adhesive contact interactions between microgear silicon-based MEMS teeth working in a clean and vacuum environment have been modelled using a multiscale hierarchical elastic structure. Here the results of numerical simulations based on the use of multiscale block model are presented. The tooth is modelled as a bulk silicon-based MEMS surface covered by roughness having two subscales specified by the character of interactions: atomic subscale level and adhesive subscale. Friction over completely meshing teeth surfaces is estimated by calculation of the total energy dissipated during sliding. The dissipation is caused by the different physical and chemical mechanisms. Due to the vacuum environment, these mechanisms reduced to the energy lost by the dissociation of chemical and van der Waals bonds, and by the elastic interlocking between the asperities located on the meshing micro-tooth surfaces. It is argued that due to the Polonsky-Keer effect, there is no plastic deformation of the MEMS tooth surface asperities because the asperity sizes are within the validity of this effect. The adhesion layer is defined employing ideas of the Maugis approximation. The adhesion force of each nanoasperity has assumed to be equal to the pull-off force in the Boussinesq-Kendall model corrected by the Borodich no-slip coefficient. The simulations show that MEMS with the clean silicon surfaces of teeth cannot work due to stiction between surfaces, while friction between tooth surfaces functionalised by carbon-based layer is much smaller. If the functionalised coating is worn away then stiction may occur.

***Keywords:*** *MEMS; microgear wear; adhesion; sliding contact; stiction.*

## 1. Introduction

Micro-Electro-Mechanical Systems (MEMS) have been used in the wide variety of industrial and space applications [1]. However, there are various challenges that may lead to device failure, in particular, these related to the stiction, adhesion and friction between various micro/nano components of MEMS that are used to transfer the load and torque [2]. Stiction is defined as the unintentional adhesion (the static friction) that highly restricts the movements of the micro/nano elements. This phenomenon may significantly reduce the MEMS reliability [3]. Microgear is one the most important torque transmitter in MEMS. When it work there is contact between the teeth. Cold welding (cohesion) between micromachined device surfaces could occur when these surfaces are clean and work in the vacuum environment [2, 4]. If the MEMS teeth are clean and work in a vacuum then there is a high probability of sticking with each other and as a result for this cold welding occurred in the contact zone, which lead finally to structure collapse. Here stiction has defined as the unintentional adhesion between the teeth that does not allow MEMS to work at all. Surface functionalisation is one of the successful solutions to reduce cohesion and, therefore, to eliminate stiction [1].

The dimension of the meshing microgear as was taken as in [5]. Figure 1 shows a micro-pinion that is meshing with micro-gear. The gap between surfaces of microgears meshing teeth, which is different at each time step, is calculated using Hertz line contact theory.

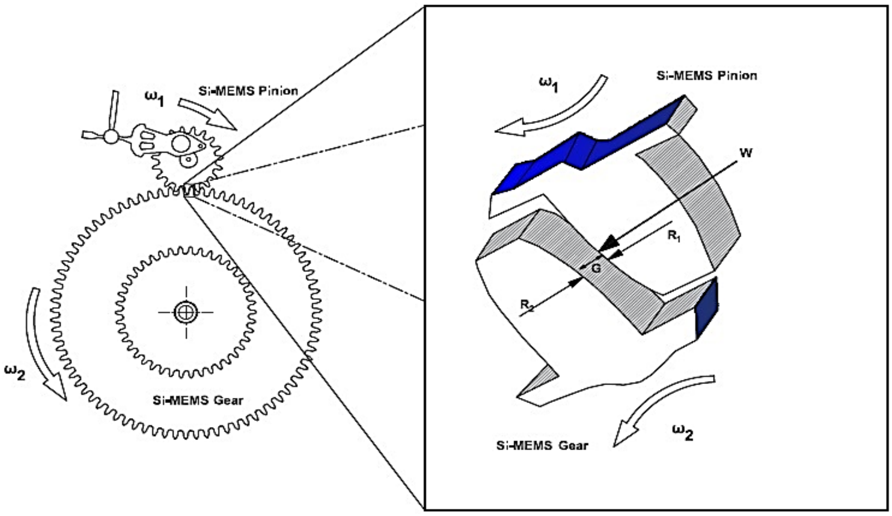

Figure 1: Microgears meshing in MEMS devices.

In this study, the term ‘scale’ is defined as the term that reflects validity of different physical-chemical mechanisms of interactions between surfaces. The multiscale hierarchical model of an asperity [6] is modified and employed in order to simulate the work of multi-asperity rough surfaces of MEMS microgear teeth as shown in Figure 2. $W_{adhesive}$ is the width of the adhesive subscale where the van der Waals interactions likely occur.

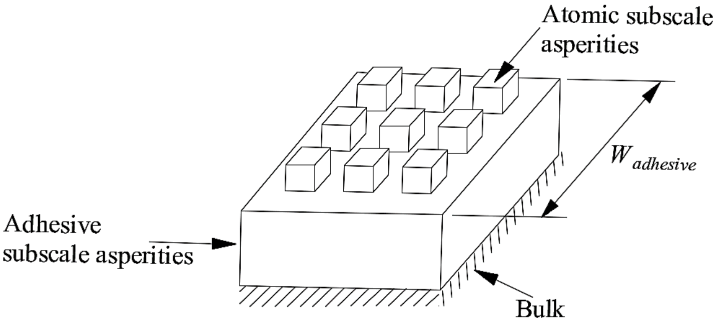

Figure 2: Multiscale hierarchical structure

Due to the nanoscale dimensions of the asperities of the microgear tooth, it does not have the micro-scale roughness. In addition, the asperities do not have plastic deformations due to the Polonsky and Keer effect [7]. Thus, the present model has two nanoscales: atomic scale as the first subscale of nanoasperity and adhesive nanoscale as another subscale. The latter subscale reflects the dimensions where the van der Waals interactions are significant.

## 2. Friction force

The friction force and the coefficient of friction are estimated over the whole meshing surfaces of the teeth. The dry friction force ($F_f$) is calculated through the energy dissipated ( $U_{diss}$ ) during relative sliding distance ($x$) between two meshed micro-tooth elastic rough surfaces.

$$F_f = U_{diss}/x \tag{1}$$

This energy lost is due to dissociation of chemical and van der Waals bonds, and the energy lost through elastic deformation of nanoasperity during the contact.

$$U_{diss=} U_{Totalchem} + U_{TotalvdW} + U_{elastic} \tag{2}$$

Then it follows from (1) and (2) that the friction force $F_f$ and the coefficient of friction $\mu$ can be calculated respectively using the following expressions

$$F_f = (U_{Totalchemical} + U_{TotalvdW} + U_{elastic})/x \tag{3}$$

$$\mu = \mu_{chemical} + \mu_{vdW} + \mu_{elastic} \tag{4}$$

The total energy loss through the different mechanisms between the counterpart's surfaces has been shown in Figure 3 and the coefficient of friction (COF) for non-functionalised teeth surfaces has been shown in Figure 4.

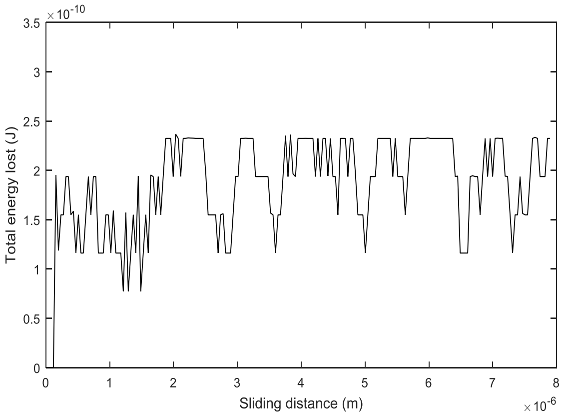

Figure 3: Total energy loss

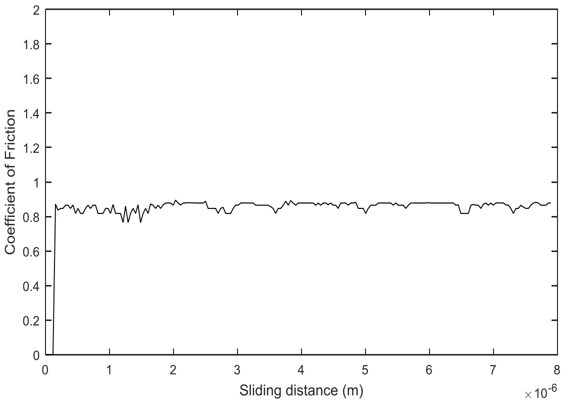

Figure 4: COF for non-functionalised teeth surfaces

Thus, as it has been mentioned, due to the vacuum environment, the energy lost the mechanisms may be reduced to the dissociation of chemical and van der Waals bonds, and the energy lost through the elastic interlocking between the asperities located on the meshing micro-tooth surfaces.

## 3. Adhesion force

The force of adhesion for one nano-asperity is assumed as the pull-off force according to Boussinesq-Kendall model, corrected with non-slip coefficient ($C_{NS}$) introduced by Borodich [8]. Let $F_{adh1}$ be the adhesion force of one asperity and *n* be the number of asperities in contact. Then one has

$$F_{adh1} = \sqrt{8\,\pi\, w_{12}\, E^* C_{NS}\, a^3}. \quad \text{Therefore} \quad F_{adh} = nF_{adh1} \tag{5), (6}$$

Where $w_{12}$ is the surface energy. For silicon, the Hamaker constant $A_{12} = 1.1 \times 10^{-18}\,J$ [9] and the separation distance between atoms $D_0 = 1.49$ Å respectively. The half width $a$ of the silicon adhesive asperity is 97.5 $nm$ . The contact modulus can be calculated by substitution the corresponding values of Young's modulus $E = 161\ GPa$, and the Poisson's ratio $\nu\ =\ 0.23$ [5, 9].

In small scale devices that having sliding interfaces such as gear MEMS, wear considerably decreases their lifetime and reliability, and stiction will stop them from working at all. Applying specific carbon-based layers, such as Octadecyltrichlorosilane self-assembly monolayer (OTS-SAM), that functionalise the micro-tooth surfaces (see Figure 5), may reduce friction and the probability of stiction and friction.

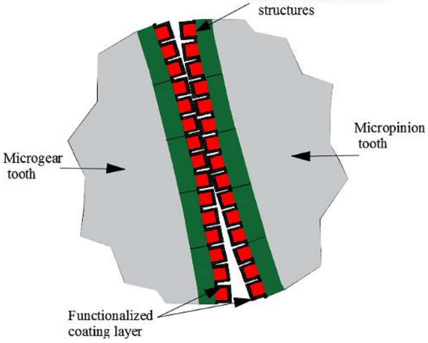

Figure 3: Functionalised coating layer covered the counterpart's microgear MEMS teeth

Indeed, it has found that the friction between the tooth surfaces functionalised by this carbon-based layer is much smaller. Then, with operation, stiction will start to occur when the coating is worn away.

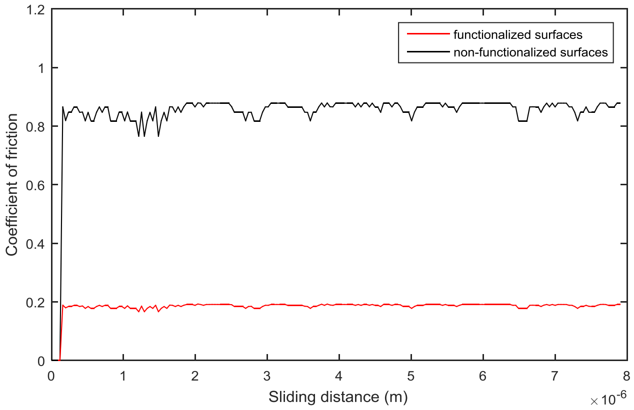

Figure 4: Comparison of the COF before and after the functionalisation of the teeth surface by OTS-SAM layer

## 4. Conclusions

A new approach to modelling of friction and adhesion between the silicon-based microgears MEMS working in a vacuum environment is described. In this approach, for the first time roughness has characterised as multi-block structures covering the entire micro-tooth surface. Each block has represented by a multiscale hierarchical asperity that consists of two different scales: atomic subscale, where the chemical interactions are significant, and adhesive subscale, where the van der Waals interactions are likely occur. The total energy dissipated due to interlocking of nano subscale asperity, dissociation of chemical and van der Waals bonds has been calculated.

Simulations have shown that the probability of stiction is very high if the gear surfaces are not functionalised. In contrast, the tooth surfaces having functionalised monolayer carbon-based coatings are much less prone to stiction. The wear of the functionalised coating leads to increase the probability of stiction between surfaces.

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