Serbian Tribology Society

SERBIATRIB '15

14th International Conference on Tribology

University of Belgrade, Faculty of Mechanical Engineering

Belgrade, Serbia, 13 – 15 May 2015

TRIBOLOGY IN MICROMECHATRONICAL DEVICES

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Abstract: *There are important connections between mechatronics and tribology, because many precision devices in mechatronics are based on tribology principles. Tribology, as the science of friction, wear and lubrication, studies principles and phenomena of the two surfaces in contact with the relative motion. Many devices function on the principle of the relative motion of their parts, therefore, the tribological and mechanical aspects are equally important in analysing these systems. Primarily, for researchers in the field of micromechatronical devices, the tribological domain is a challenging field. It has been observed that the development of sliding micromechatronical systems has several limiting factors such as friction, stiction and wear. These factors influence systems efficiency and stability. This paper is dedicated to describe the tribology processes in microelectromechanical and nanoelectromechanical systems, and emphasize the ways in which it is possible to achieve a reduction of friction, wear or adhesion. The special attention in this paper will be paid to a newly developed compliant microgripper, as a representative of micromechatronical devices with tribology effects. Stiction represents a special problem in microgrippers since adhesion can occur between gripper fingers and the grasping object preventing the gripper to continue its function. Moreover, in the comb drive system that is used to drive the microgripper, stiction can occur between comb fingers.*

Keywords: *microelectromechanical systems, nanoelectromechanical systems, friction, stiction, microgripper, comb drive*

1. INTRODUCTION

The engineers try to reduce the size of the devices and to improve performances of the system in the miniaturization process. Many devices today applied in printers, computer, robotics, medical equipment, are very small in size. Regardless of their size they work with high efficiency, they are low-cost and they have high functionality. This miniaturization to micro scale led to the fact that micromechatronics became an important technology field. The micro-electromechanical systems (MEMS) is an emerging field of technology and new area which enabled many types of sensor, actuator and system to be reduced in size by orders of magnitude [1]. The field of MEMS already have a great influence on our lives and became very attractive because of the small mass and size, low power consumption and low cost production [2-4].

Further devices reduction to nano scale resulted in creating the nanotechnology and nanomechatronics [5]. The micro-nano mechatronics is very important for many technologies, such as material science, energy, and control. Friction, lubrication or adhesion [6], received special attention in recent developments of MEMS and nano-electromechanical devices (NEMS), microsystems and nanotechnology. The commercialization of MEMS/NEMS devices is slower than scientists expected, commonly because the behaviour of microscopic components is different than the behaviour on the macroscopic level, due to big difference between the properties of bulk materials and their micro or nano forms [1]. An overview of the state of the art in MEMS/NEMS is given in the literature [7].

When two surfaces are in relative motion the mechanisms of the interactions between them range from atomic to microscale. Those processes need to be well understood because it could help better explication of fundamental physical and tribological phenomena – adhesion, friction, lubrication and wear. The interfacial phenomenon in micro/nanostructures can be explained by findings in nanotribology and nanoscale mechanics and make an important connection between science and engineering [8]. Nanotribology after macro and micro tribology is the scientific area which has received considerable attention in the last few decades. This is because molecular tribology (or nanotribology) includes phenomena related to the interaction between molecules and atoms and connected interatomic phenomena, determined by the physical and chemical structures of materials [9]. The quantum mechanical effect and some other mechanical effects should be taken into account to describe the occurrences at nanoscale [10].

When solid surfaces are in contact the tribological phenomena such as adhesion, friction, and wear arise, especially when the size of devices is on micro- and nanoscales [11]. It has been observed that at low normal forces adhesion is an important friction mechanism, which is supported by many experimental results [12]. Adhesive interactions are present in many miniature devices, such as comb drives and microgrippers which are the subject of our special interest. Comb-drives are capacitive actuators which usually operate at the micro- or nano-meter scale. The microscale adhesion in MEMS has been often described and reviewed in the literature [13]. Unwanted adhesion, known as stiction, is a frequent failure mechanism in MEMS, especially under special environmental conditions [13-17]. The clarification of reasons why friction and stiction are very dominant in small size devices is large surface area to volume ratios in MEMS and NEMS [18,19].

The strong adhesion, friction and wear too, are phenomena with a big influence on the lifetime of many MEMS devices. Due to the size of MEMS, the numerous surface forces such as capillary, electrostatic, Van der Waals forces, and many others, have an influence on adhesion. Therefore, there is a need for better understanding of interactions between micromachined surfaces when the distance between them is very small [10]. Despite the enormous success in solving problems in MEMS, some technological issues need greater attention, particularly when the topic is stiction phenomena [20].

Tribological and static interfacial forces are comparable with forces driving device motion in MEMS and the macroscale lubrication methods are inapplicable. Therefore, new nano-engineering approaches must be employed for MEMS devices with moving structures. In order to ensure operational reliability and to enhance efficiency, stiction and friction have to be usually reduced, what is crucially importance in MEMS and NEMS with contacting surfaces in relative motion. For that purpose, lubricants are employed between the surfaces. Because a contact between surfaces occurs in numerous asperities, the research of two contact surfaces, especially at the molecular level and the friction phenomenon at the nanometer scale, need a special attention of nanotribology.

The boundary lubrication regime is defined when the distance between surfaces is a few nanometers what is equal to few molecular layers. Anorganic self-assembled monolayers (SAMs) is good model systems for boundary lubrication. The ultrathin organic films of usually defined thickness can be realised by self-assembled monolayers preparation [21]. More recently, lubrication in a small-size system, such as MEMS or NEMS is a big challenge in scientific work, especially in the study of new kind of lubricants. Different type of monolayers attached to sliding surfaces appears as a good candidate in MEMS lubrication [21]. Therefore, the understanding of behaviour between monolayers films is of great importance in tribological and nanotribological experiments. The recent results in this coating technology are presented by authors [16]. The boundary films have been the subject of study for decades, since friction and wear phenomena are affected by these ultrathin films. Under friction, the dynamics of lubricants on surfaces is very important, especially the molecular behaviour of lubricants in boundary lubrication. There is also special interest in the possibility of manufacturing molecular layers with particular properties. Molecular self-assembly is recognized as a powerful strategy for the fabrication of nanoscale structures.

For the nanotribological studies of few nanometers thick monolayers, new devices have been designed. The surface force apparatus (SFA) was made many decades ago (1968) and is usually applied to study properties of molecularly thin films confined between two molecularly smooth surfaces. The scanning tunnelling microscopes (STM), invented in 1981 allows imaging some surfaces with atomic resolution, as well as of lubricant molecules. The introduction of the atomic force microscopes (AFM) in 1985 gave an opportunity for measuring very small forces between a probe tip and surface in order to give information about morphology of the surface and surface roughness on the nanoscale, and for adhesion measurements [22]. With the development of a number of powerful techniques in surface analysis, as mentioned above, academic interest in SAMs has regained, because of the possibilities to investigate the growth and the structure of such layers on the nanometer scale. Thin microtribological coating are today investigated and applied to improve microtribological properties of MEMS, with a special attention on coating material selection, the process of their preparation and further optimisation require significant attention [23].

SAMs have been already applied in MEMS and NEMS as the anti-stiction layer [15]. It has been demonstrated the advantages of this way of the surface contact prevention, pointing out the influence of many experimental parameters such as temperature and surface roughness.

As it is mentioned above, comb-drive actuators are one of the most fundamental designs in the field of MEMS [24]. One very important and almost unavoidable problem in MEMS is stiction, which occurs when the interfacial forces cannot be overcome by the restoring forces of the microstructures. Stiction could compromise the performance and reliability of the MEMS devices or may even make them malfunction. In order to solve this problem, the failure modes and failure mechanisms of these microdevices must be understand better. Problem of stiction is often divided into two types: the adhesion during the process of fabrication and the adhesion after the application of the device, more fully described in the literature [25]. The new techniques in which device stiction in comb-drive actuator can be overcome have been described in the paper [26].

The special attention in this paper will be paid to a newly developed compliant microgripper, as a representative of micromechatronical devices with tribology effects. Stiction represents a special problem in microgrippers since adhesion can occur between gripper fingers and the grasping object preventing the gripper to continue its function. Moreover, in the comb drive system that is used to drive the microgripper, stiction can also occur between comb fingers.

2. DEVELOPMENT OF COMPLIANT MICROGRIPPER

In the precision industries and micro engineering such as micro assembly, micro robotics, electronics, optics, drug delivery, tissue manipulation and minimally invasive surgery, precise manipulation of microsized components are needed [27-34]. Moreover, in different fields of medicine, manipulation of biological cells and the other fragile objects is required [30]. Precision and soft manipulation is achieved based on the appropriate mechanism design of micro devices such as microgrippers. Microgripper is micro-electro-mechanical-system (MEMS) that consists of a pair of jaws for grasping and holding the micro object, actuators to provide input displacement and mechanisms for transmitting the motion from actuator to jaws. The use of conventional rigid-body mechanism with rigid-body joints (revolute and prismatic) at micro level of microgripper leads to inaccuracy in motion due to backlash, wear, manufacturing error, assembly error and friction between the assembled parts. Compliant mechanisms [35] offer one alternative for developing microgrippers and can overcome many disadvantages of conventional mechanisms.

A compliant mechanism can be defined as a single-piece flexible structure which uses elastic deformation to achieve force and motion transmission [35]. Compliant mechanisms differ from conventional rigid-link mechanisms in that they gain their mobility from the deflection of the flexible members, contain no pin joints and are intentionally flexible.

A compliant mechanism is a combination of a structure and a mechanism, since the jointless feature resembles a structure, while the function of the structure resembles a mechanism. Compliant mechanisms are designed to be flexible enough to transmit motions, yet stiff enough to withstand external loads. The transition from the conventional mechanism to the compliant one is shown in Fig. 1. The function of both the grippers is to transfer the input force to the output and to grasp an object. While the rigid-link gripper gains functionality by a rigid-body mechanism, the compliant one undergoes elastic deformations due to an input actuation.

The main advantages of compliant mechanisms over classical ones are: simplified manufacturing, reduced assembly costs, no wear, no backlash, reduced noise, easier maintenance, no need for lubrication, built-in restoring force, better scalability (possible miniaturization) and accuracy.

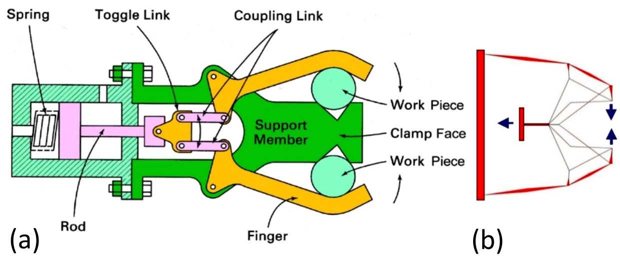

Figure 1. (a) rigid-link gripper and (b) compliant gripper [36]

Because of these advantages compliant mechanisms are used in many applications including manufacturing, aerospace, robotics, biomedical devices, grippers, motion amplifiers, positioning devices, adaptive structures, shape morphing structures, surgical tools, etc. (see e.g. [36-38]). Due to their many advantages compliant mechanisms are especially suitable for developing MEMS devices and microgrippers. Thus to develop microgripper that can perform precise manipulation of microsized components we used compliant mechanisms. The synthesis methodology used to develop compliant microgripper is described in the following section.

2.1 Synthesis methodology

Compliant mechanisms can be subdivided into two groups: mechanisms with lumped compliance and mechanisms with distributed compliance [35,36,39]. To develop microgripper we use compliant mechanisms with distributed compliance. Mechanisms with distributed compliance (Figs. 2, 4, and 5) make use of longer and thicker bending elements with the objective of better distributing the strain and stress over the structure (compared to mechanism with lumped compliance which are prone to high stresses and reduced fatigue life). Compliant mechanisms with distributed compliance gain their mobility through elastic deformation of flexible members and compliance is distributed more or less equally in the entire mechanism (i.e. they deform as a whole).

The continuum synthesis approach is usually used for the design of mechanisms with distributed compliance [40-44]. The synthesis methodology used in this approach involves two stages: generation of the mechanism topology and determination of optimum size, geometry, and shape of various constituent elements of the mechanism (dimensional synthesis). In this paper we pay more attention to topology optimization, because this is a more difficult and “creative” part of the design process. The allowable space for the design in a topology optimization problem is called the design domain (Fig. 2a). The topology is defined by the distribution of material and void within the design domain or as the pattern of connectivity of elements in a structure (Fig. 2b). The continuum based approach focuses on the determination of the optimal topology (the best material connectivity in a compliant structure). The designer only needs to define the size of the design domain in which the mechanism should fit, location of the supports, input and output ports, size of applied loads (Fig. 2a) as well as properties of the material from which the mechanism should be produced. Then, through the topology optimization, the optimal structural form (optimal topology) of a compliant mechanism for a specified input force and output deflection requirements is automatically generated (Fig. 2b).

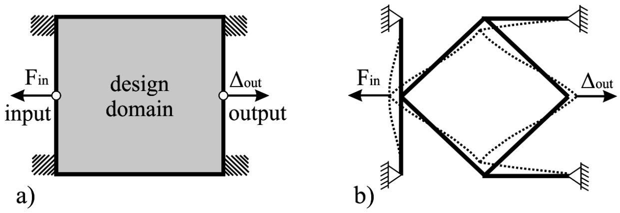

Figure 2. Synthesis of compliant displacement inverter in which the input force F_{in} and the output displacement Δ_{out} are in opposite directions: (a) design domain and (b) optimal topology of compliant displacement inverter (deformed position is shown with dash lines) [45]

In [46] Milojević et al. (2013) have developed computer-coded algorithm for synthesis of compliant mechanisms with distributed compliance, and Milojević and Pavlović (2013) improved the topology optimization technique in [45]. By using the improved topology optimization technique the compliant gripper for meso applications is already developed in [45] (Fig. 3). In this paper we scale down the compliant gripper to micro level so that it can be used as microgripper for manipulation of microsized components. Detailed explanation of how the compliant gripper is developed is given in [45].

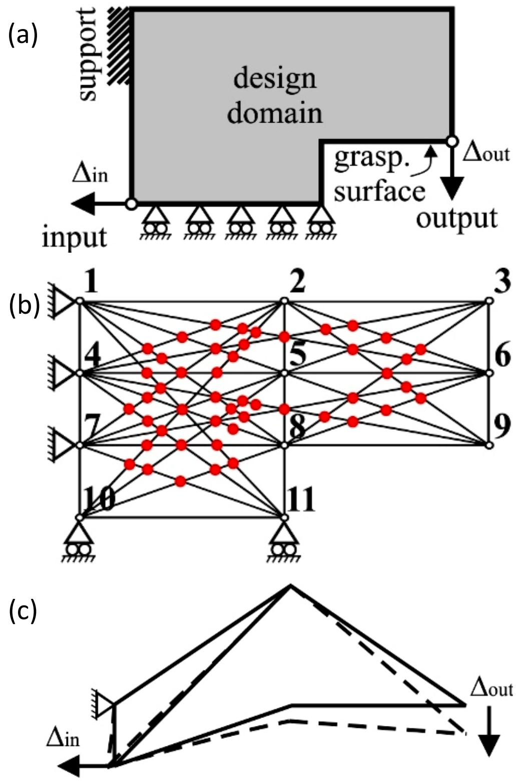

Figure 3. The steps in the synthesis methodology: (a) problem specifications, (b) parameterization (intersections between elements are indicated by red dots) and (c) optimized topology of compliant microgripper [45]

2.2 FEM analysis of the compliant microgripper

Based on the obtained solution (Fig. 3c), a 3D solid model of the two fingered compliant microgripper was designed (Fig. 4).

To investigate the capability of this microgripper to achieve gripping of microsized components, FEM simulations were performed; the commercially available FEM software was used. As a boundary condition, a fixed support was applied at the immobile part of the microgripper (Fig. 5a). As an input a displacement of 1 μm was introduced in the *x* direction at the input port of microgripper (Fig. 5a), and output displacement was measured in both *y* and *x* direction at the output port (Fig. 5a).

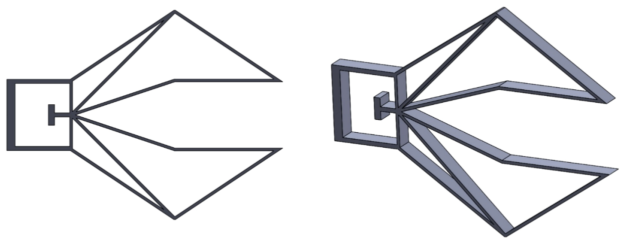

Figure 4. 3D solid model of the two fingered compliant microgripper

The FEM results show that the compliant microgripper is capable of grasping different microsized components with gripping range of 24 μm (Fig. 5b). The geometrical advantage of microgripper is Δ_{out}/Δ_{in} = 6.37 μm and displacement in the *x* direction at the output port is 0.32 μm (Fig. 3c).

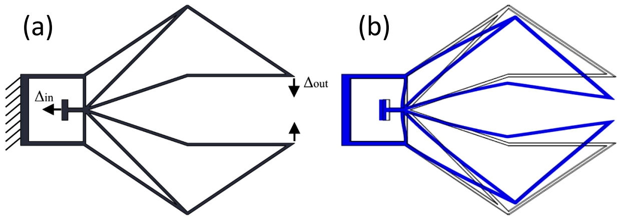

Figure 5. Design of compliant mirogripper (a) and FEM results when input displacement is applied (b)

To supply an input displacement to microgripper an actuator is needed. Various actuation techniques have been used such as electro-thermal actuators [47], electrostatic actuators [48], piezo-electric actuators [49], electro-magnetic actuators [50], SMA actuators [51], and fluidic micro actuators [52]. We decided to use comb drive system [24] as actuator for compliant microgripper. Comb drives (Fig. 6) are electrostatic capacitive microactuators in MEMS that are comprised of arrays of parallel plates arranged into opposing comb pairs, where one comb in each pair is rigidly fixed to the substrate (the fixed comb), and the other comb is fixed to the substrate through a spring structure (the movable comb) [53]. When a voltage difference is applied between the fixed and movable combs the electrostatic forces generated between them attract the movable combs towards the fixed combs. When the voltage difference is removed the springs restore the movable combs to their original positions. Comb drive actuators have many applications in different MEMS devices [24] because they provide highly linear, in-plane motion, in relatively large range (typically up to 50 μm) and have high accuracy movement.

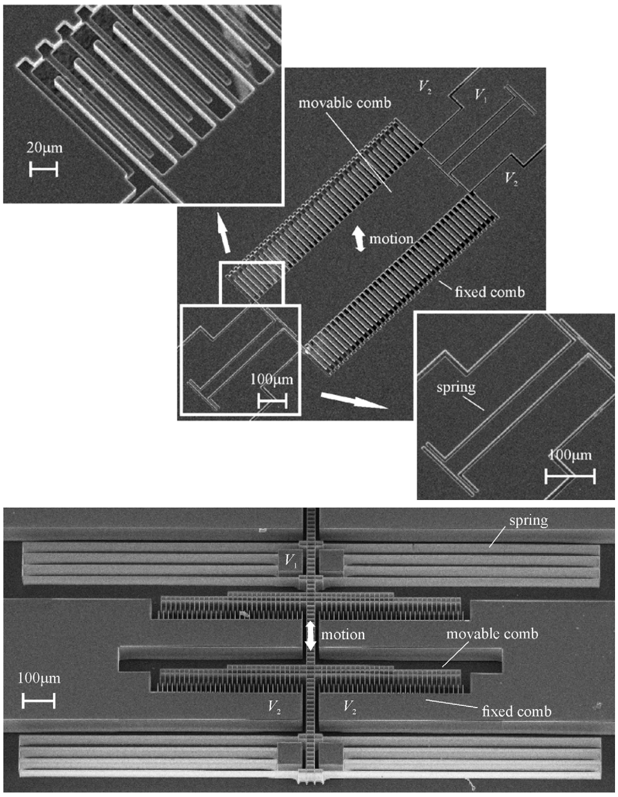

Figure 6. Comb drive actuator [53]

Conceptual design of compliant microgripper with comb drive actuator is shown in Figure 7a. Comb drive actuator consist of one fixed comb with array of 30 parallel plates/fingers and one movable comb (with array of 29 parallel plates/fingers) opposing the first comb where movable comb is a part of microgripper structure. When a voltage difference is applied between the two combs the generated electrostatic forces attract the movable comb towards the fixed comb and thus provide the actuation for microgripper (Fig. 7b).

3. POSSIBILITY OF STICTION PROBLEM ELIMINATION WITH SELF-ASSEMBLY MONOLAYERS IN COMPLIANT MICROGRIPPER WITH COMB DRIVE ACTUATOR

In micro physics, the surface forces such as Van der Waals forces and electro static forces are influencing more than the inertial forces like gravitational force. In the case of microgripper surface forces often can be larger than elastic forces of the compliant mechanism. Surface forces can cause adhesion between gripper fingers and the grasping object (stiction occurs) and prevent microgripper for returning to its equilibrium state. In the comb drive system that we used to drive the microgripper, stiction also can occur between comb fingers.

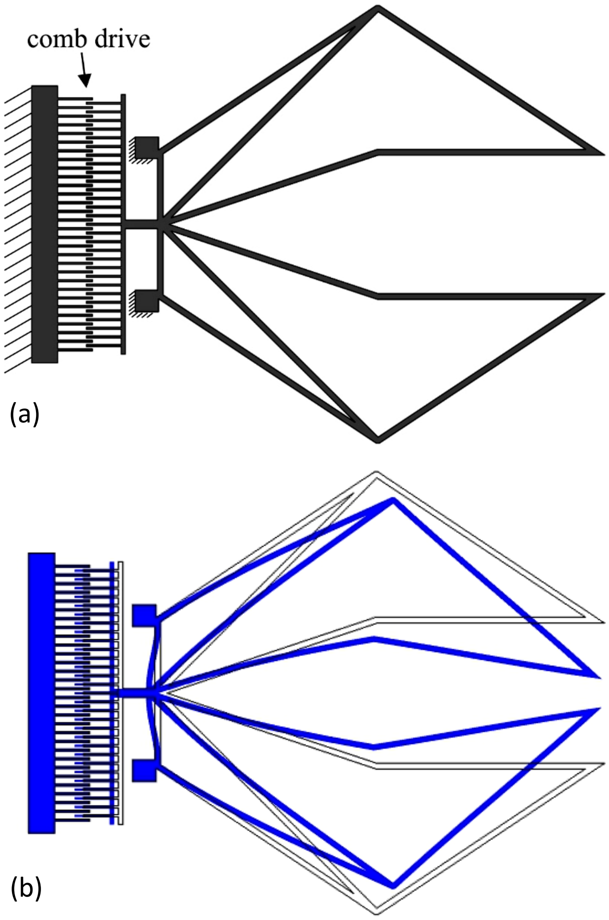

Figure 7. (a) conceptual design of compliant microgripper with comb drive actuator and (b) working principle

In order to reduce stiction few methods have been suggested or applied, which is already described in the literature [15]. It has been shown in experimental analysis that SAMs can change some surface properties listed by many authors [15,54]. Several classes of organic films have been investigated, such as alkyil- and perfluoroalkytrichlorosilane SAMs, dichlorosilane- and alkene based molecular films. These chemical compositions proposed as a promising surface coatings for MEMS. A review of parameters important for some anti-stiction coatings was described together with criteria important for stiction [15]. To avoid stiction in MEMS, sometimes is useful to make some numerical analysis and create the numerical models to make this kind of failure predictable and avoidable. A micro-macromulti-scale approach was developed and described [55] in order to predict possible stiction of MEMS devices.

In order to eliminate stiction in compliant microgripper and comb drive system SAMs could be used. SAMs as monolayer technique are especially attractive and able to solve stiction problems, as confirmed by others [16]. Grasping surface of compliant gripper could be coated with self-assembled monolayers as well as surface of comb drive fingers (Figure 8). Further investigation is needed to determine which of SAMs is appropriate as coating to eliminate stiction which will be done in the future.

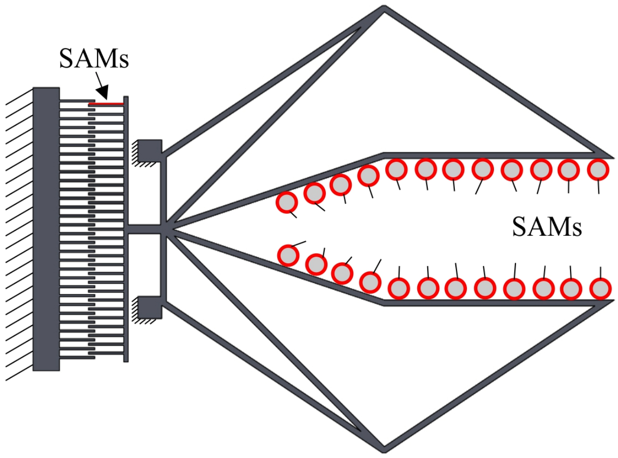

Figure 8. Compliant microgripper with comb drive actuator coated with SAMs

4. CONCLUSION

In this paper the new compliant microgripper with comb drive system as actuator was presented. Stiction can often occur between gripper fingers and the grasping object and in the comb drive system between comb drive fingers. Several experimental results described in the literature have indicated the possibility of solving this tribological problem present in MEMS and NEMS. Results in MEMS where stiction was considered helped to better understand the fundamental phenomena in nanoscale, such as friction or adhesion. Our idea was to point out how the problem of stiction was solved, taking into account also the possibility to overcome this problem in our MEMS, compliant microgripper and comb drive system with appropriate SAMs structure.

The choice of the appropriate SAMs structure with the optimal chemical and mechanical properties will be a task for our future work.

ACKNOWLEDGEMENT

This research has been supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Project HUMANISM, code III44004 – Intelligent Human-Machine Mechatronic System for Medical Applications).

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