INFLUENCE OF THE FLEXURE HINGE SHAPE ON COMPLIANT GRIPPER SMALL DISPLACEMENTS

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Abstract. This paper proposes a new model of compliant gripper used to micromanipulate small objects. The gripper is designed with 16 flexible hinges of the same shape and the same overall dimensions. The influence of the lengths of the kinematic elements on the displacement amplification is studied. The shape of the flexible hinges is an essential factor in the final displacement of the tweezers. So, it was analyzed the displacement for: corner filleted with different radii, circular, elliptic and parabolic shape. Compliant mechanisms perform differently depending on the elasticity of the materials from which they are made, so this aspect is also analyzed. Finally, the results obtained from the finite element analysis are presented comparatively.

Key words: Compliant mechanism, flexible hinge shape, finite elements analysis, materials, displacement.

1. INTRODUCTION

In recent years, a trend for miniaturizing products such as in microelectromechanical system (MEMS) can be observed [1–4]. This approach has intensified general research on automated micromanipulation and microassembly techniques. The development of miniaturized systems for manipulating and assembling microobjects has become a great challenge in precision engineering [5–8]. Microgrippers are preferred to other mechanisms for micromanipulation and assembly due to their ability to grasp objects of different shapes with a higher precision [9–12]. The microgrippers have many applications in materials science, medicine – biological and tissue manipulation, microelectronics etc. Taking this into account, it is very important to design and develop new high-performance microgrippers in order to accomplish the requirements of new micromanipulation and microassembling operations.

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Compliant mechanisms achieve their mobility due to the relative flexibility of their compliant joints [13]. Using compliant joints in a mechanism structure leads to a lot of advantages: a mechanism can be built in one piece, the weight can be reduced and wear, clearance, friction, noise and need for lubrication can be eliminated [14–19]. Therefore, these compliant mechanisms are suitable to be applied in micromachining and micropositioning [20–22]. On the other hand, the mechanisms with compliant joints can realize relatively small displacements so their mobility is limited.

Numerous studies have been performed on the design of microgrippers having different specifications. One of the most important components in designing a microgripper is displacement transmission mechanisms. Being a critical component of microgrippers, it has an important influence on the characteristics of the microgripper. Because the output displacement of the smart actuator is small, it needs to be amplified by the displacement transmission mechanisms [23–26].

This paper presents the design, modeling, and optimization of a new microgripper actuated with piezoelectric (PZT) actuator. The compliant microgripper has a structure of flexure-based amplification and the study was performed for various shapes, lengths of the kinematic elements and different materials.

2. THE GRIPPER DESIGN

The study begins with a general 3D model with stack piezoelectric (PZT) actuator and a compliant gripper designed with 16 flexible hinges of the same shape and the same overall dimensions as it can be seen in Fig. 1.

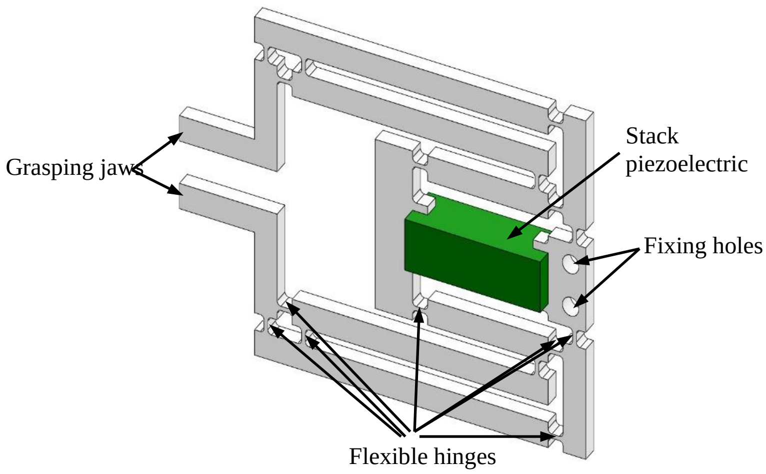

Fig. 1 – 3D model of the PZT driven microgripper.

Fig. 1 shows the grasping system consisting of a stack PZT ceramic actuator, a pair of grasping jaws and the compliant mechanism. To get large jaw displacements, the displacement transmission mechanism is designed as a structure of flexure hinges that realizes amplification.

In the beginning of the study, the right corner filleted flexure hinges are considered, since they are more precise in keeping the positions of the rotation centers compared to the others [27]. The microgripper is designed symmetrically along the longitudinal axis of the PZT actuator to avoid shear force and bending torque acting on the PZT actuator.

For analytical model it is necessary to realize a Pseudo-Rigid-Body Model. Fig. 2 shows the corresponding kinematic chain for the proposed PZT driven microgripper.

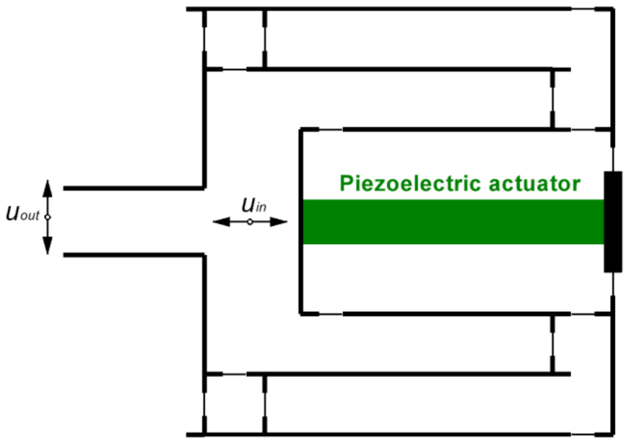

Fig. 2 – Kinematic chain of the PZT-driven microgripper.

The boundary conditions at the fixed end A of the PZT actuator are:

$$u_{Ax} = 0,\ u_{Ay} = 0,\ \theta_A = 0. \tag{1}$$

Castigliano's theorem can be used to find reactions and displacements; for instance:

$$u_{Ax} = \frac{\partial U}{\partial R_{Ax}} = \sum_{j=1}^{5}\left(\int_0^l \frac{N_j}{EA(x)} \frac{\partial N_j}{\partial R_{Ax}} dx_j + \int_0^l \frac{M_j}{EI(x)} \frac{\partial M_j}{\partial R_{Ax}} dx_j \right) \tag{2}$$

The displacement amplification is results as the ratio of the output displacement to the input displacement:

$$m.a. = \frac{\Delta y}{\Delta x} = \frac{u_{out}}{u_{in}}. \tag{3}$$

The piezoelectric stack actuator has hysteresis in functioning, as such, for the numerical analysis input values it was necessary to test it. The resulting displacements versus applied voltage are presented in Fig. 3.

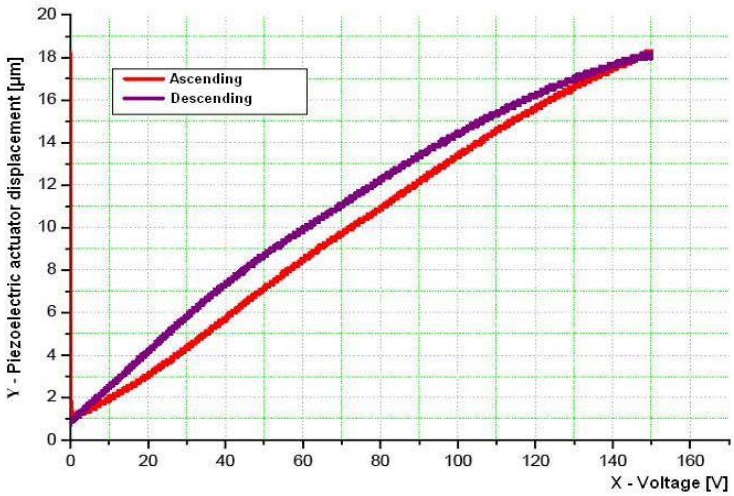

Fig. 3 – Piezoelectric actuator parameters after testing.

The experimental piezoactuator data has subsequently been used as input to the compliant gripper.

The objective of the study is to design the compliant microgripper for different specific micromanipulation applications. For optimization purposes, several variants, which influence the functioning characteristics of compliant gripper, must be taken into consideration, Fig. 4.

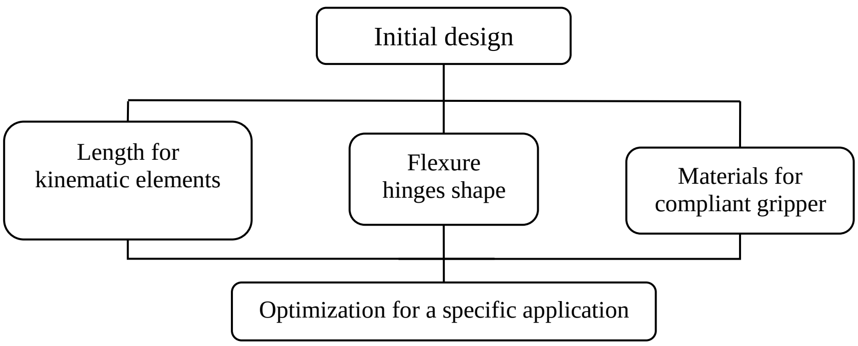

Fig. 4 – Schematic representation of the variants for numerical study.

For a given application, where specific conditions are needed, in order to obtain required amplification displacements and von Misses stress in the flexible hinge, the numerical study needs to take into consideration the following:

- the values for individual length of kinematic elements in order to maintain the overall dimensions of the compliant gripper fixed.
- the shape of the flexure hinges, which can determine the transmission of different displacements/forces at the end effectors,
- the materials for compliant grippers can improve the elasticity/rigidity.

3. THE INFLUENCE OF INDIVIDUAL LENGTH OF KINEMATIC ELEMENTS ON COMPLIANT GRIPPER PERFORMANCE

The characteristics of the optimized microgripper are investigated using Simulation module of the SolidWorks software based on finite element analysis (FEA). An alloy steel was adopted as the material of microgripper to appropriate mechanical properties, namely high elasticity, good toughness, and moderate strength. In the process of simulation, the 3D solid model built in SolidWorks was imported into the Simulation module for mesh generation: boundary conditions and static loads were applied and then a static analysis was carried out. For the flexible part of the flexure hinges of the microgripper, a small mesh generation parameter was set, and for the other parts the mesh was generated automatically, which can accurately describe these parameters to improve the accuracy of the analysis results, accelerate the analysis speed and save time.

The boundary conditions and load application position are shown in Fig 5.

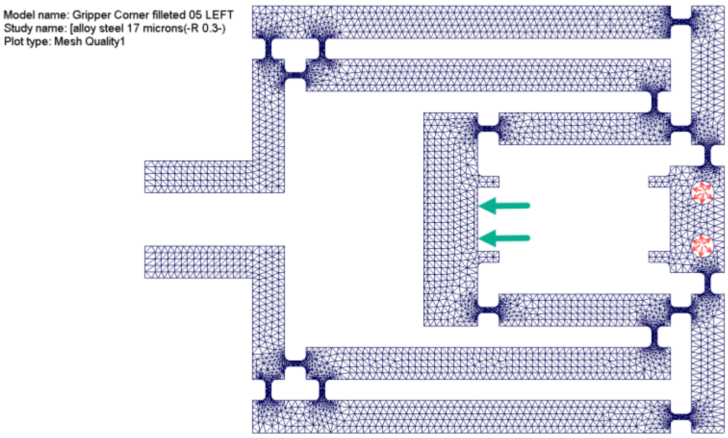

Fig. 5 – Fixtures (red) and applied displacement (green).

The parameters of the microgripper material are as follows: the material was Alloy Steel with an elastic modulus E = 210 GPa, Poisson's ratio ν = 0.28, yield strength σ = 620.422 MPa and density ρ=7700 kg/m^3. A displacement of 17 μm was applied at the input end, based on the piezoelectric actuator parameters (see Fig. 3). The displacement diagram of the microgripper is shown in Fig. 6.

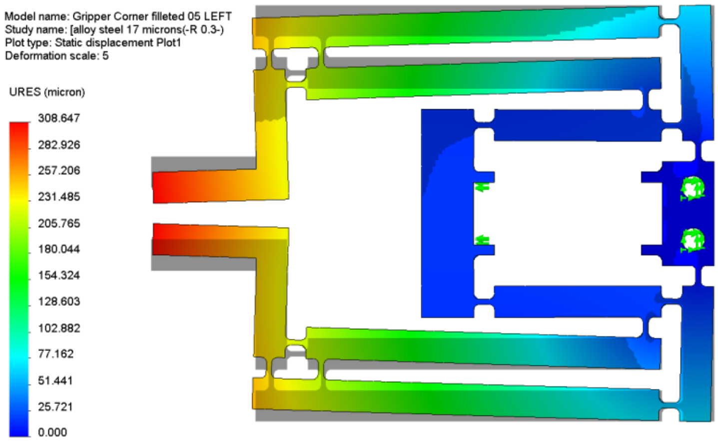

Fig. 6 – Resultant displacement diagram.

The output displacement of the microgripper was 308.647 μm and the displacement amplification was 18.155 times.

As shown in Fig. 7, the maximum stress was concentrated on the flexible hinges of the mechanism, in which the maximum value was 278 MPa, which is less than the yield strength of the material (620 MPa). Therefore, the mechanism can be used safely, there is no yield failure in the actual use.

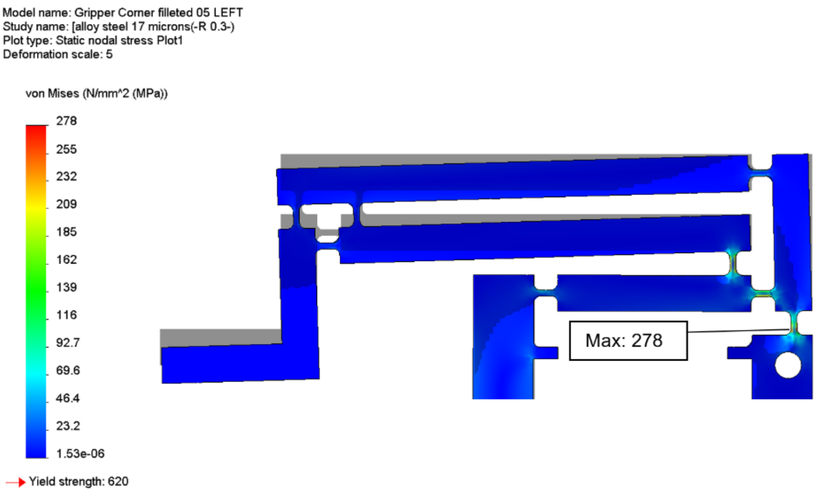

Fig. 7 – Stress (von Mises) diagram.

The individual length of kinematic elements influences the compliant gripper performance. To obtain different lengths of the kinematic elements, the position of the flexure hinge was modified in the FEM studies, Fig. 8.

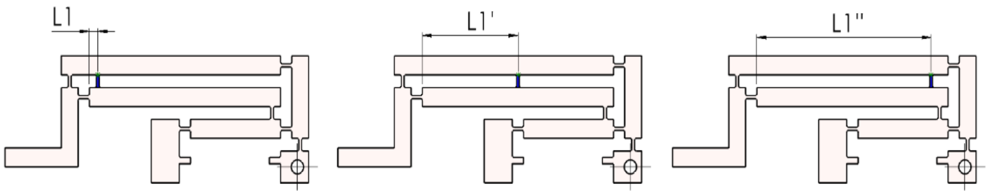

Fig. 8 – Three different lengths of the kinematic elements.

The lengths of the kinematic elements were L1 = 1.5 mm, L1' = 17 mm and L1" = 31 mm. The simulations were carried out for an increment of 0.2 μm for PZT actuator displacement resulting in 9 simulations for each variant of microgripper.

The results obtained for L1' were 65.43% better than for L1'' and for L1 were 75.04% better than L1", or 1.75 times better for L1' compared with L1'' and 1.07 times better for L1 compared with L1'.

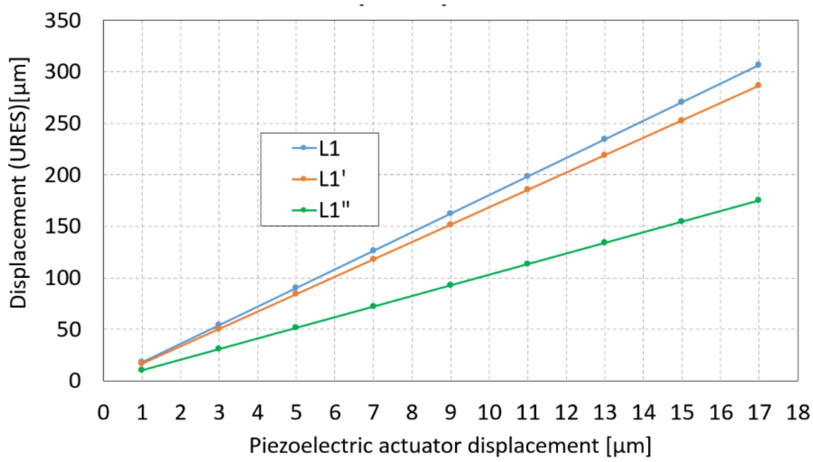

Fig. 9 – Influence of the kinematic elements' length on the output displacement.

As it can be seen in Fig. 9 the best results in terms of resulting displacement at the end of grasping jaws were obtained for L1 length of the kinematic element. So, further simulations for evaluating other parameters of the microgripper will be made considering L1 as the default length of the kinematic element.

In order to verify the translational gripping effect of the microgripper, a 17 μm input displacement was imposed on the microgripper.

Fig. 10 shows the displacement diagram of the gripping jaws of the microgripper. The output displacement of the gripping jaw of the microgripper increases gradually from the bottom to tip. The output displacement was maximum (308.647 μm) at the tip of the gripping jaw and minimum (230.020) μm at the bottom.

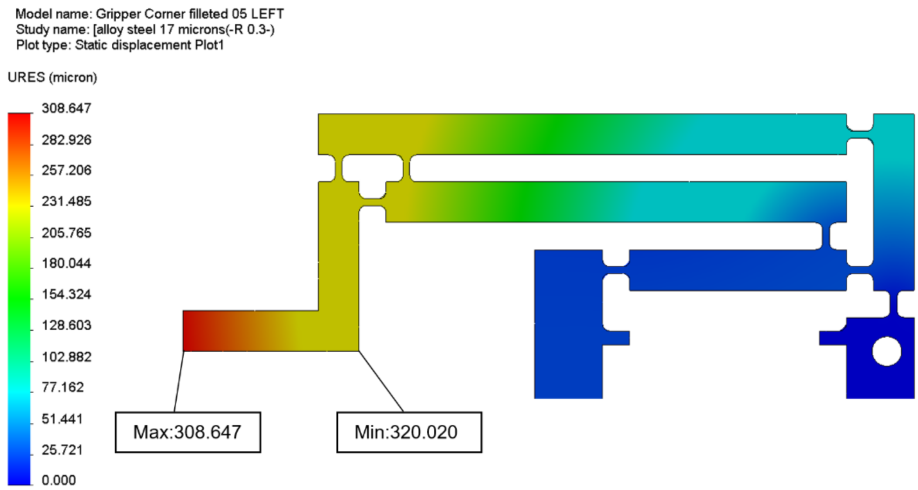

Fig. 10 – The displacement diagram of the gripping jaws.

4. THE STUDY FOR VARIOUS FLEXURE HINGE SHAPES

Flexure hinges are the most important components in compliant mechanisms because they achieve smooth precision motion, are virtually free of backlash, hysteresis and friction. Flexure hinges act as elastic joints, directly connect two adjacent rigid members, and provide mobility by their elastic deformation. Besides, flexure-based monolithic mechanisms are lightweight, compact, tractable and low-cost. Numerous methods have been introduced to model hinge compliances, including analytical, numerical and empirical ones [28–29].

Each type of profiles provides unique mechanical properties to suit different requirements of design [29], such as different levels of stress concentration, out-of-plane stiffness, or discrepant motion accuracy. Four types of flexure hinges, namely: corner-filleted flexure hinges, circular flexure hinges, elliptical flexure hinges and parabolic flexure hinges, are chosen for the analysis at first, Fig. 11.

The unconventional manufacturing technologies such as Additive Fabrication, LIGA technology for MEMs etc., permits any notch shape to be achieved. The shape of the flexure hinge notches can therefore be chosen based on the design requirements for specific application. Flexure hinges undergo elastic deformation relative to adjacent stiffer regions in compliant mechanisms.

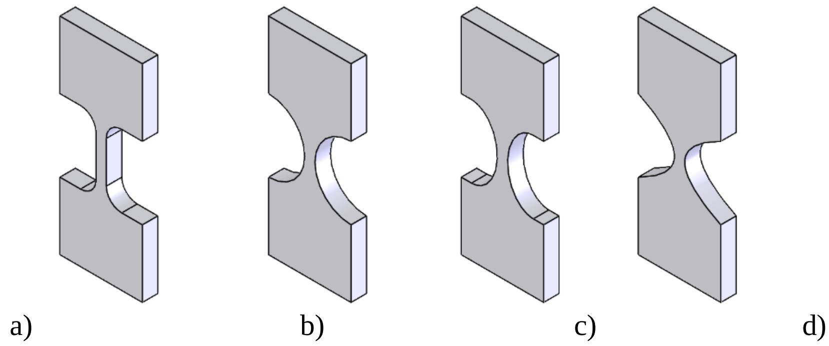

Fig. 11 – Typical notch flexure hinges: a - corner-filleted, b – circular, c – elliptical, d – parabolic.

The difference of compliance and stiffness is reached by geometric characteristics of deformation regions. Depending on these characteristics, flexure hinges are designed with single or multiple axes. Notch-type flexure hinges with single axis are often profiled as rectangular section, circular, corner filleted, elliptic, parabolic, hyperbolic or other conic profiles and hybrid cross sections.

The simulations were carried out for the same increment of 0.2 μm for PZT actuator displacement.

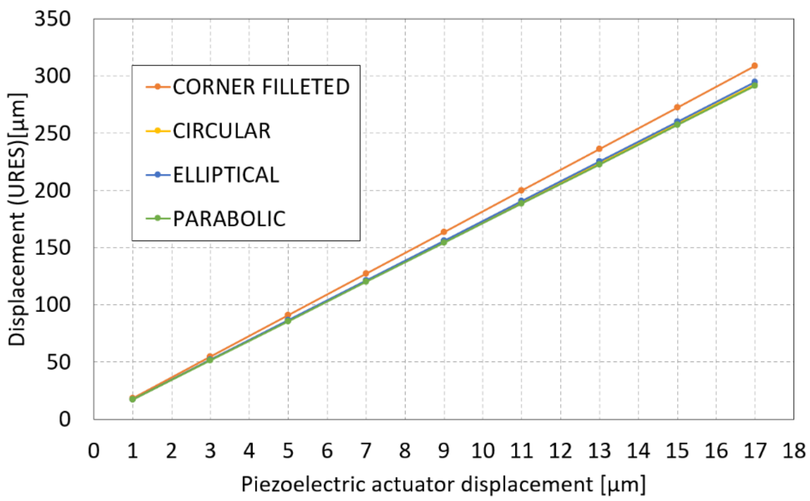

Fig. 12 – Influence of the flexure hinges geometry on the output displacement.

As it can be seen in Fig. 12 the best results in terms of resulting displacement at the end of grasping jaws were obtained for corner filleted shape of the flexure hinges. This shape of the flexure hinges was considered as default for the next simulations for evaluating other parameters of the microgripper.

The next set of simulations was carried out to determine which is the best value for the radius of the corner filleted flexure hinge for the proposed microgripper.

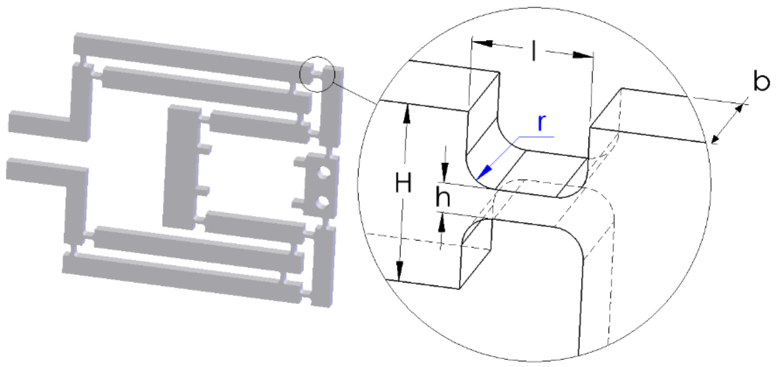

Fig. 13 – Model and basic hinge dimensions of the flexure hinges.

As stated at the beginning of this study there the gripper has 16 flexure hinges of the same shape and size. The aim of the next FEA investigation was to determine the influence of the parameter r on the resultant displacement at the tip of the grasping jaws. The other geometrical dimensions of the hinge were considered fixed: hinge length l = 2 mm, hinge height H = 3 mm, hinge width b = 2 mm and minimal notch height h = 0.5 mm, Fig. 13. The values for the radius were r = 0.3 … 0.75 mm with an increment of 0.05 mm. The results obtained, for a 17 μm PZT actuator displacement, after the FEA are presented in Fig. 14.

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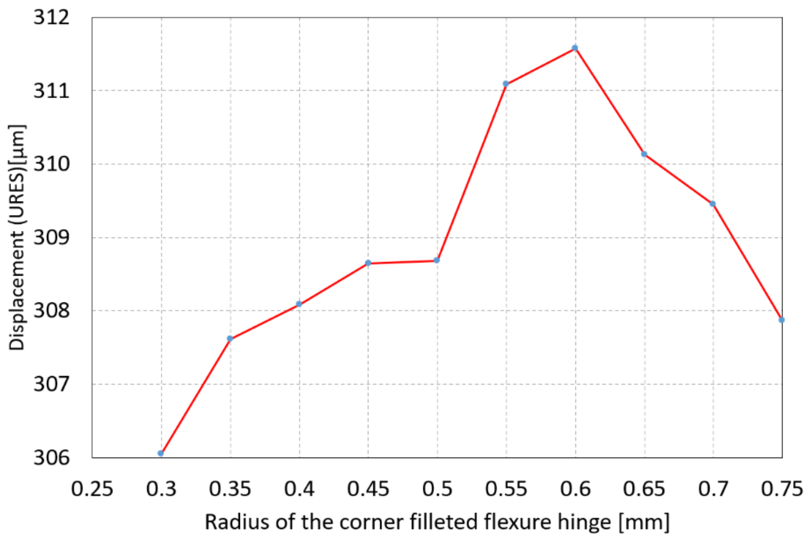

Fig. 14 – Influence of the corner filleted radius value on the output displacement.

Depending on the fillet radius, different maximum displacements values result for the same notch length. Also, as FEA results indicated, those very small radii cause a stress concentration at the corners of the notch. A large fillet radius leads to a significant increase of the stress which appears mainly in the center of the notch. The studies, carried out according to the mentioned assumptions, pointed out to similar displacements for various values of the fillet radius, but the most favorable value that was obtained for r = 0.6 mm.

Increasing the number of joints in the kinematic chain results in lower guiding errors as well as lower stress values, while the qualitative characteristics remain the same. The notch contour has a strong influence on the motion range and precision in the case of multi-bar compliant mechanisms.

Considering all the investigations mentioned above, the final model of the gripper with the largest displacement at the end effector with the overall dimensions is presented in Fig. 15.

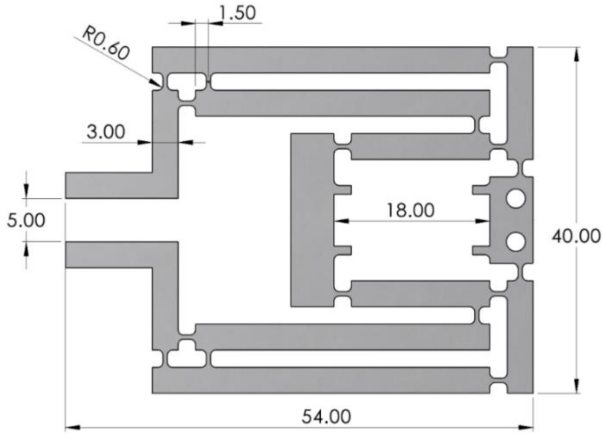

Fig. 15 – Final model of the PZT driven microgripper.

5. COMPARISON FOR FIVE CONSTITUENT MATERIALS

Compliant mechanisms perform differently depending on the elasticity of the materials from which they are made. A high aspect ratio is usually required for microgrippers to realize high out-of-plane stiffnesses and ensure the safe positioning of micro-objects. Various types of constituent materials have been introduced in the fabrication of compliant microgrippers.

With the final shape and dimensions for the model of the microgripper established, Fig. 15, there was made another set of FEA analyses in which five different materials were studied. The average strength characteristics of materials that have been given in the finite element software are summarized in Table 1.

Table 1

The average strength characteristics of assigned materials.

Property	Description	Value					Units
		Alloy Steel	***PMMA***	***PTFE***	***Brass***	***POM***	
EX	Elastic modulus	210000	3000	599	100000	2400	MPa
NUXY	Poisson’s ratio	0.28	0.35	0.46	0.33	0.35	-
GXY	Shear modulus	79000	890	230	37000	890	MPa
DENS	Mass density	7700	1200	2320	8500	1200	kg/m^3
SIGXT	Tensile strength	723.8	73	30.5	478.4	517	MPa
SIGYLD	Yield stress	620.4	45	131	239.6	206.9	MPa

where: *PMMA* – Polymethylmethacrylate; *PTFE* – Polytetrafluoroethylene; *POM* – Polyoxymethylene.

These materials were chosen because they are normally used for different applications in different environments. Grasping and manipulating small or micro-objects is required for a wide range of essential applications, such as the assembly of small parts in microsystems or microsurgery, microbiology. Manipulation of micrometer- and nanometer-scale biomaterials and integrating them into different microsystems have become critical issues in the bio nanotechnology field. One of the requirements for microgrippers is that they should not contaminate the components or environment during the operation.

Fig. 16 shows a comparison of the results obtained for the displacement at the tips of the grasping jaws when a 17 μm PZT actuator displacement is applied. The results are in a very small range of values, a maximum difference of 1.43 % was obtained between the different materials for compliant microgripper.

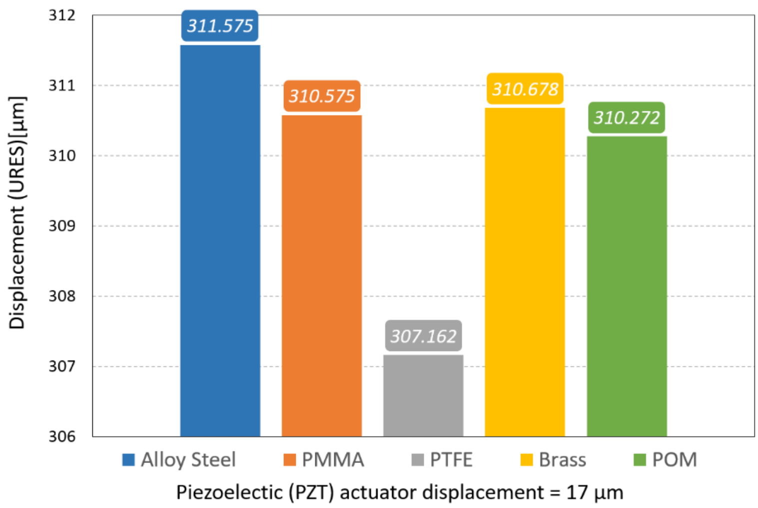

Fig. 16 – Comparison of the PZT driven microgripper made of different materials.

6. CONCLUSIONS

The paper presents an original compliant microgripper with 16 flexure hinges and stack piezoelectric actuator. After the study about the influence of the lengths of the kinematic elements on the displacement amplifications, the best model for a maximum displacement was chosen.

Four types of flexure hinges: corner-filleted flexure hinges, circular flexure hinges, elliptical flexure hinges and parabolic flexure hinges, were analyzed. The best results in terms of the displacement at the end of grasping jaws were obtained for corner filleted shape for r = 0.6 mm.

In the end, the displacements of the compliant microgripper jaws were analyzed for Alloy Steel, Polymethylmethacrylate, Polytetrafluoroethylene, Brass and Polyoxymethylene and the best result obtained was for Alloy steel.

In the future the compliant microgripper will be tested and an algorithm for control will be established.

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