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Elastic inflatable soft actuators for electrochemical machining on internal surfaces of metallic workpieces

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Abstract
Soft actuators exhibit high mechanical compliance allowing a variety of deformation modes. This property makes them interesting candidates for force-free micromachining processes such as electrochemical machining (ECM) and electro-discharge machining (EDM). ECM in particular has high potential to utilize soft actuators as a tool as this process does not involve machining forces and is absent of tool wear. In this paper, the design and development of a soft actuator prototype is presented that allows for enhanced control of the interelectrode gap (IEG), along with a conductive element to be used for ECM applications.

Keywords: Micromachining, Electrochemical Machining, ECM, soft-actuators, soft-machines, soft-tools, soft-robotics.

1. Introduction

Soft robotic systems [1] are built from silicone rubbers or other materials with high mechanical compliance, and are actuated using a pressurized fluid, usually air or water. They have been gaining increasing research interest in the 21st century thanks to their potential applications across various length scales [2] such as low Reynold's number fluid propulsion, biomimicking structures, minimally invasive surgery, active prosthetics and handling of delicate objects. The compliance, fast actuation times, wide modes of actuation (bending, twisting, contraction and expansion), embedded motion path and flexibility in positioning makes them interesting candidates for force-free micromachining processes such as Electrochemical Machining (ECM) [3] and Electro-discharge machining (EDM). Furthermore, the ECM process is absent of tool wear, contrary to EDM, giving it a particulary high potential for integration with soft actuators.

Soft machines [4], which are soft actuators that integrate ECM (Fig. 1(a)) [5] or EDM functionalities, will help in minimizing the use of multiple motion axes and their complex control softwares in ECM machine tools. Additionally, they will simplify the design of tools for machining at hard-to-reach locations, such as corners, bends, narrow-spaces, bearing races, spacing between gear teeth, etc. This will reduce the machine tool and tooling costs and will help to downsize machine tools, making them more portable as well. However, in order to employ soft actuators in precise machining applications, several challenges need to be fulfilled concerning the design and fabrication of such actuators as well as their positioning accuracy.

This work in particular will focus on the machining of internal features on metallic workpieces using in-house fabricated soft actuators. A preliminary research work is presented on the development of soft actuators with embedded conductive elements to be used for electrochemical machining applications. The design and development of a soft actuator is presented along with proof-of-concept electrochemical machining on a prototype workpiece.

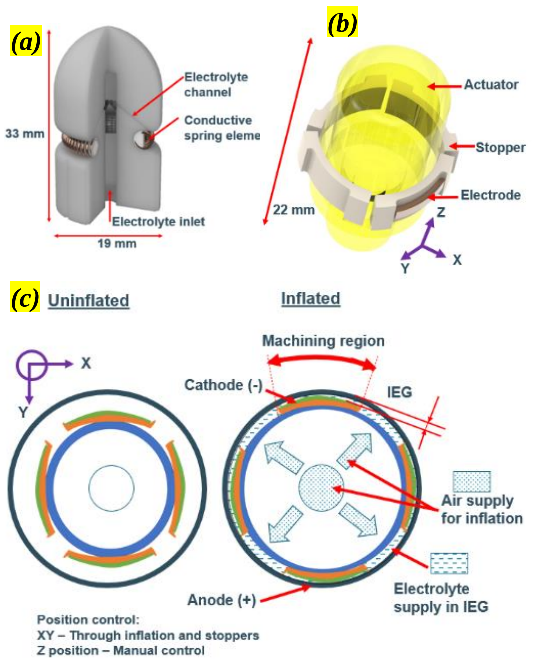

Figure 1. (a) Previously reported [5] soft-actuator (b) Newly designed soft actuator with enhanced stroke and IEG control. (c) Schematic of the electrochemical machining process with soft-actuator in (b) inside a cylindrical workpiece. IEG refers to interelectrode gap between the cathodic tool and anodic workpiece.

2. Design of the soft actuator

The new actuator design, which is depicted in Figure 1(b), focusses on impoving stroke and IEG control. The new soft actuator is comprised of a silicone rubber hollow cylinder, to which four PMMA stoppers are mounted. Each stopper houses a metal wire as the cathodic tool-electrode for the ECM process. During this process, the actuator is placed inside a hollow cylindrical metal workpiece, which is used as the anode. By inflating the actuator with pressurized air, it expands and moves the stoppers with electrodes radially outwards into the workpiece, as is shown in Figure 1(b). In the presence of electrolyte, an electrically conductive path forms between the metal wire cathodes and the metal workpiece anode, resulting in material removal from the workpiece. By integrating stoppers into the soft actuator design, positioning accuracy of the tool-electrode with respect to the workpiece is no longer determined by the deformation of the soft actuator. Instead, the actuator is now inflated until protrusions on the stoppers touch the workpiece. These protrusions extend further radially outwards than the tool-electrodes, meaning that the IEG is directly determined by their length measured from the outmost surface of the tool-electrodes. In other words, the stoppers are a strictly mechanical solution to solve the issue of IEG control and eliminate the need for precise control of the soft actuator deformation.

3. Manufacturing of soft-actuator

The soft-actuator is cast out of DragonSkin® 10 silicone rubber using two sets 3D printed PLA moulds (Fig. 2(a)). For each set of moulds, liquid silicone rubber is first poured into one halve of the mould and the other halve is then pressed into it, shaping the actuator part inside of it. Next, the silicone is left to cure inside the moulds until solid, after which it is cast out. Then, the two actuator parts are glued together using Sil-Poxy® silicone glue and a latex air supply tube is attached using additional silicone glue, resulting in an airtight soft actuator ready for inflation. Finally, PMMA stoppers are mounted to the actuator using Cyanoacrylate glue, as well as a metal wire. The design shown in Figure 1 was adapted slightly to facilitate these glueing postprocessing steps that have to be carried out manually. Instead of glueing smaller metal wires on top of the stoppers, one longer wire is glued directly to the actuator. Regardless, the conceptual working principle remains the same. Figure 2(b) shows first prototype of the produced soft-actuator.

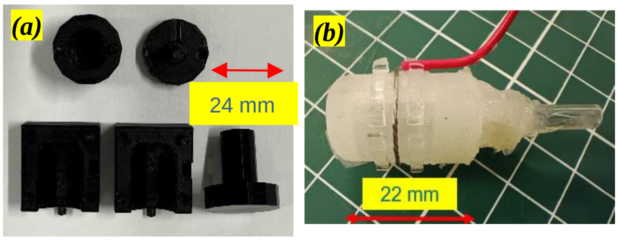

Figure 2. (a) 3D printed mould of PLA. (b) Prototype of produced soft actuator.

4. Machined footprints of ECM using soft actuator

Pilot machining experiments were done on the internal surface of a cylindrical stainless steel workpiece using 20% aq. NaCl (sodium chloride) as electrolyte. The main machining parameters were: voltage levels 6, 20, 25 V, pulse on time of 10 µs with a duty cycle of 50 %, electrolyte flow rate of 0.3 mL/s, interelectrode gap of 500 µm and the duration of machining was set as 30 s. Figure 3(a) shows a representative picture of the machined footprints at different voltage levels using the soft actuator in Fig. 2(b). It was observed that at voltage levels of 20 and 25 V, the machining was not stable due to limited elecytrolyte flow and excessive Joule heat accumulation in the IEG as the machining currents reached > 10 A and black Fe_3O_4 formed at 25 V (Ra 2.9 µm). This also affected stability of inflated actuator. At 6 V, machining was stable (Ra 1.9 µm) and current remained nearly constant (~ 2 A) since the actuator could expand to compensate for the increase in IEG as observed from Figure 3(b). The observed machining footprints reveal that the soft-actuator was not able to maintain uniform current density over the entire circumference of cylindrical workpiece as more electrolyte could accumulate in the gaps between the stoppers of the actuator leading to uneven dissolution. Therefore, a twisting actuator will be added as the next step to rotate the soft-tool along with a constant current source to maintain uniform current density along the entire periphery of the workpiece. Furthermore, for achieving high quality polishing it is of utmost importance to form a dissolution product film on the surface of anode which requires pulse on times of around 10 ms and pulse interval of around 50 ms. For the applied pulse on time of 10 µs, the product salt film cannot form and hence, polishing phenomenon cannot be observed. Further research is underway to improve both the soft-actuator and the ECM polishing parameters.

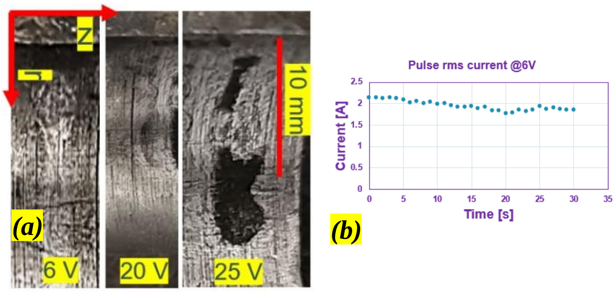

Figure 3. (a) Footprints of ECM process on the inside of a cylindrical stainless steel workpiece (b) Evolution of machining current (I_{rms}) at 6 V.

5. Summary

This work is a fundamental exploratory research focussed on applications of soft robotic actuators for force-free machining processes (such as ECM). In this work, a new soft actuator (22 x 16 mm) was designed and fabricated to achieve better interelectrode gap (IEG) control required for ECM process. The design specifications and production process has been discussed along with ECM pilot experiments on the inside of a cylindrical stainless steel workpiece. Further work is planned for improving the design of the actuator along with improving the ECM performance.

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