A Monolithic Shape Memory Alloy Microgripper for 3-D Assembly of Tissue Engineering Scaffolds

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ABSTRACT

This paper describes a microgripper used for the micro-assembly of an artificial scaffold for tissue engineering. The porous sponge-like scaffold is a three dimensional construct built by tiny unit parts of biodegradable polymer. This application requires the assembly of several parts by applying a suitable level of force. In this framework, a monolithic shape memory alloy (SMA) microgripper was developed. It consists of two small fingers for grasping, an active part that changes its shape when heated and a parallel elastic structure used as a bias spring. The main aspect of the design is that all these elements are included within a single piece of material, but have different mechanical properties, and are used for different functions. Using a new technology of Shape Memory Alloy laser annealing developed at EPFL, a local shape memory effect is introduced on the active part while leaving the remaining areas in a state where no shape memory effect occurs, i.e., in a cold-worked state. The parallel elastic structure is used to provide a pullback force on cooling as well as to guide the finger movement. An electrical path is integrated to heat the active part and drive the gripper by Joule effect.

This paper focuses on the principle of the micro-gripper, its design and describes the fabrication process. Some first experimental results are also presented.

Keywords: Microgripper, Microassembly, Shape Memory Alloy (SMA), Scaffold, Tissue Engineering.

1. INTRODUCTION

Tissue engineering aims at applying engineering and life science to investigate the relationships between structure and function of different tissues. Over the last years, tissue regeneration using biodegradable scaffolds has become one of the most promising techniques to replace grafts. Porous, sponge-like scaffolds or three dimensional (3D) constructs provide support for cells and growth factors to attach, proliferate and maintain their differentiated function, and its architecture defines the ultimate shape of the artificial tissue [1] (Fig. 1). The performance of the biodegradable scaffold depends on the ability to integrate living cells and growing factors with the desired distribution and to produce scaffolds composed of different materials.

Our project will produce 3-D scaffolds by assembling tiny unit parts [2]. In this way it will become possible to control the distribution of the material, living cells and growing factors inside the scaffold. To simplify the design and assembly, we have selected Lego®-like parts that can be pushed down from above, needing the control of only 4 degrees of freedom. By applying a suitable level of force, parts are fixed together by friction.

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The micro-gripper has to grasp the $0.42 \times 0.42 \times 0.06$mm parts (Fig. 2) and assemble them in the scaffold (Fig. 3). Based on previous simulation, the force required for this assembly is within a few mN. Although this simulation cannot consider all the effects due to the small dimensions of our elements, it gives us a first specification for the gripper. Considering the size of the unit part and the scaffold structure, the available working space does not exceed 180 µm. In addition, as the thickness of the unit part may vary around 60 µm, a motion range of 70 µm is specified.

Recently there has been an increasing interest in tooling to build micro-mechanical parts and systems, and research in the scaling down of actuators has been carried out to give an idea of which types of actuators are suitable for the actuation of micro-mechanical systems [3]. It has been generally acknowledged that shape memory alloy actuators can attain a high power/weight ratio of about 100 W/kg, while even DC motors have difficulty in exceeding the level of 10 W/kg for actuator weighting less than 100g [4].
Considering our requirements, we have chosen a gripper technology based on Shape Memory Alloys (SMA). Shape memory refers to the ability of certain materials to “remember” a shape, even after rather severe deformations: once deformed at low temperatures (in their martensite phase), the material will stay deformed until heated, whereupon they will spontaneously return to their original shape [5]. However, the shape memory effect is not intrinsically reversible: once the shape has been recovered by heating after a deformation in its low temperature phase, the material does not change its shape again on cooling. This is the so-called “one-way” shape memory effect.

To make the shape memory actuator reversible, two methods are generally used. The first one uses a thermo-mechanical treatment, i.e., a training process, on the material in order to obtain a spontaneous shape change on cooling. This method has been successfully applied for actuating micro-grippers [6]. The other method uses a bias spring to deform the material on cooling. This method is the most widely used for SMA actuators. Using a concept of monolithic design [7] and a new technology of Local Annealing of SMA (LASMA) [8], the second method was chosen to develop a suitable microgripper.

In this work, the second method was chosen and applied on a monolithic design. Thanks to the new technology of Local Laser Annealing, the shape memory effect is introduced to the active part of the micro-gripper, while the other parallel structure serves as a bias spring and guiding system. The following sections of this paper will detail the design principle of this gripper, the fabrication procedures and some experimental results.

2. DESIGN OF THE PARALLEL SMA MICROGRIPPER

1. Generalized design using one-way shape memory effect

a. Working principle

b. Stiffness characteristics of the actuating spring and the bias spring

Fig. 4: Design principle: A shape memory actuating spring is working against a bias spring

The design of shape memory actuators is based on the different stress-strain curves of the material in its austenite and martensite state. Fig. 4a shows the principle of our design. Fig. 4b illustrates the stiffness characteristics of the actuating spring and the bias spring. Although the mechanical characteristics are non-linear, straight lines are displayed to simplify the representation. In Fig. 4b, the x-axis shows the compressive displacement of the springs from their stress-free state while the y-axis indicates the force.

The first step is to introduce a pre-strain (part II in Fig. 4a). The actuating spring is deformed at a given low temperature in the martensite state causing the equilibrium point to move from 0 to \( P_1 \). When the actuator is heated up to the austenite/martensite phase transformation temperature, it tries to recover its original shape (part I in Fig. 4a). Since the transformation induces a change of mechanical characteristics, new equilibrium points of the coupled design are formed from \( P_1 \) to \( P_3 \) respectively, and inducing the motion of the actuator (part III in Fig. 4a). On cooling, the actuator
transforms back to the martensite phase. Due to the force applied on the actuator by the bias spring, the equilibrium point moves back from P₁ to P₃ (part IV in Fig. 4a) producing the reverse motion of the actuator.

2. Actuator and bias spring design
As mentioned before, the mechanical characteristics of the actuating spring is non-linear. The actuator must be deformed until martensitic variants reorientation occurs. Therefore, the behavior of the coupled system is very difficult to predict. However, reasonable assumption can be done by calculating the extreme points (P₁, P₃) by linearizing the mechanical characteristics of the material for these specific points. Usually we set the high temperature equilibrium point in the pure elastic domain of stress-strain curve of austenite phase. The actuating force and reset force at high temperature are chosen somewhat arbitrarily and several design calculations may be required to determine optimum geometry for the shape memory and the bias springs. Some examples of calculations are proposed in Table 1. The first shape is chosen as the actuator (Fig. 5a) because it can produce larger deformations within a relatively smaller space and allows further miniaturization of the gripper. Compared to the third shape, for the same dimensions and a minimum bar width of 70 µm, the stiffness of the first shape is about one ninth of the third shape. The fourth shape is selected as bias spring because its structure has the intrinsic property to guide the motion of the finger.

Table 1: \( I = \frac{b^3 h}{12} \)

<table>
<thead>
<tr>
<th>Geometry (deform under a constraint of displacement)</th>
<th>Stiffness (using classical elastic theory)</th>
<th>Maximum Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <img src="image1.png" alt="Geometry 1" /> ( \delta )</td>
<td>( K = \frac{3EI}{L^3} )</td>
<td>P: ( M = \frac{2FL}{3} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q: ( M = \frac{FL}{3} )</td>
</tr>
<tr>
<td>2. <img src="image2.png" alt="Geometry 2" /> ( L ) ( R ) ( \theta ) ( \delta )</td>
<td>( K = \frac{6EI(L + R\theta)}{L^2 \sin^2 \theta[L^2 + 4LR\theta + 6R^2(1 - \cos \theta)]} )</td>
<td>L&gt;&gt;R: ( M_{\text{max}} = \frac{F \sin \theta}{(L + R\theta)} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \frac{L^2}{2} + LR\theta + R^2(1 - \cos \theta) )</td>
</tr>
<tr>
<td>3. <img src="image3.png" alt="Geometry 3" /> ( \delta )</td>
<td>( K = \frac{3.36EI}{R^3} )</td>
<td>( M = \frac{2FR}{\pi} )</td>
</tr>
<tr>
<td>4. <img src="image4.png" alt="Geometry 4" /> ( \delta )</td>
<td>( K = \frac{2AEI}{L^3} )</td>
<td>( M = \frac{FL}{4} )</td>
</tr>
</tbody>
</table>
3. Design calculations

Let $K_\text{a}^u$ and $K_\text{a}^m$ be the actuator stiffness in austenite and martensite phases respectively.

$K_\text{a}^u$ and $K_\text{a}^m$ write:

$$K_\text{a}^u = \frac{3E_\text{a}I_\text{a}}{L_\text{a}} \quad K_\text{a}^m = \frac{3E_\text{m}I_\text{m}}{L_\text{m}} \quad \text{with} \quad I = \frac{b'h}{12}$$

Where $E_\text{a}$ and $E_\text{m}$ are the Young’s modulus in austenite and martensite, $I_\text{a}$ and $I_\text{m}$ are the inertia of the actuator and the bias spring. $L_\text{a}$ and $L_\text{m}$ are the length (as shown in the figures in Table 1). $b$ and $h$ are the bar width and bar thickness respectively.

We assume: $K_\text{a}^u = 2K_\text{a}^m$ and $K_\text{a}^u = 2K_\text{a}^m$

The stiffness of the bias spring writes:

$$K_\text{b} = \frac{4E_\text{b}I_\text{b}}{L_\text{b}}$$

Where $E_\text{b}$ indicates the Young’s modulus of the bias spring and $I_\text{b}$ its inertia and $L_\text{b}$ its length.

We assume: $E_\text{b} = E_\text{a}^u = \frac{1}{2} E_\text{a}^u$

Theoretically, $E_\text{b}$ should be equal to $E_\text{a}^u$. But in practice, as it will be further discussed in Section 4, the stiffness seems lower than expected, this is why we have introduced a correction factor of 0.5.

A maximum displacement of 210µm ($\delta_{\text{max}}^u$) to the bias spring was chosen. Since the motion range should be 70µm, the prestrain for the bias spring has to be 140µm ($\delta_p^u$).

Let $\delta_\text{a}^u$ and $\delta_\text{a}^m$ be the compressive displacements of the actuator in austenite and martensite states, respectively.

The condition for equilibrium in austenite writes:

$$K_\text{a}^u \cdot \delta_\text{a}^u = K_\text{a} \cdot \delta_{\text{max}}^u$$

(1)

While the condition for equilibrium in martensite writes:

$$K_\text{a}^m \cdot \delta_\text{a}^m = K_\text{a} \cdot \delta_p^m$$

(2)

Thus by dividing (1) by (2), we obtain:

$$\frac{K_\text{a}^u}{K_\text{a}^m} \cdot \frac{\delta_\text{a}^u}{\delta_\text{a}^m} = \frac{\delta_{\text{max}}^u}{\delta_p^m} = \frac{3}{2}$$

$$\frac{\delta_\text{a}^u}{\delta_\text{a}^m} = \frac{3}{4}$$

As $\delta_{\text{max}}^u - \delta_p^u = 70\mu m$, $\delta_\text{a}^u$ and $\delta_\text{a}^m$ are known:

$$\delta_\text{a}^m = 280\mu m \quad \delta_\text{a}^u = 210\mu m$$

Thus the prestrain on the structure writes: $\delta_{\text{max}}^u + \delta_p^u = 420\mu m$

From (1): $\frac{K_\text{a}^u}{K_\text{a}} = \delta_{\text{max}}^u = 1$ and $\delta_p^m = \delta_\text{a}^m / 4L_\text{a}$.

We choose $b_\text{a} = 70\mu m \quad L_\text{a} = 900\mu m$.

The bias spring should work in elastic domain, i.e., the maximum displacement of bias spring is 210µm corresponding to a maximum elastic strain ($\epsilon_{\text{max}}$) of 1% is then:

$$\frac{L_\text{a}^2 \cdot \epsilon_{\text{max}}}{3L_\text{b}} = 210\mu m \quad \Rightarrow \quad b_\text{a} = 140\mu m \quad L_\text{a} = 3000\mu m$$

The maximum elastic displacement of the actuator corresponding to a maximum elastic strain ($\epsilon_{\text{max}}$) of 1% writes:
Thus the actuator is deformed until martensitic variants reorientation occurs when a prestrain of 280µm is applied.

4. **Working principle of the gripper**

After local annealing, the actuating spring transforms to the martensite phase, while the remaining part is still in a cold-worked state. A prestrain is introduced to pre-deform the springs (Fig. 5b), then both sides marked A and B are fixed on a support. The gripper is heated by Joule effect. An electrical path is formed between the two contact pads, A and B. When heated to the transformation temperature, the actuator transforms from martensite to austenite and tries to recover its original shape, then pushes the two fingers to close (Fig. 5c). On cooling, the actuator goes back to the martensite phase and is deformed under the force of the bias spring, causing the two fingers to open (Fig. 5d).

Fig. 5: The design and working principle of the gripper (The two zones, marked A and B, are fixed on a ceramic plate by gluing leaving the remaining parts free)
3. **FABRICATION PROCEDURES**

There are several commercially available groups of shape memory alloys for actuator applications. In our case, Nickel-Titanium-Copper (Ni-Ti-Cu) is preferred because of its narrow transformation hysteresis and a good fatigue behavior.

The fabrication of the gripper involves the following steps (Fig. 6):

1. A Ni-Ti-Cu sheet is used. The composition of the material is Ni 49.2, Ti 44.8, Cu 6 in wt%, provided by @MT Technologies in Belgium. The sheet was produced by cold-rolling at about 20 ~ 30%.

2. The whole structure is laser-cut from the non-annealed Ni-Ti-Cu sheet (Fig. 6a). A frame is used to hold the gripper, and to prevent it from damaging during the fabrication steps. The Nd-YAG zig-zag high power slab laser was used for the micro-cutting [9][10]. This laser has a minimum kerf width of 20 to 30 µm. Pulse energy up to 300mJ with duration of 200 µs can be obtained in a quasi gaussian fundamental mode beam (M² < 1.5). The mean output power is up to 15 W that permits cutting at speeds as high as 1 mm/s.

![a. The structure after laser cutting](image)

![b. Local annealing by laser](image)

**Fig. 6: Fabrication steps of the SMA microgripper**

3. The actuating spring is locally annealed (Fig. 6b) to recover the phase transformation partially damaged during the cold-rolling. The center of the laser beam is set close to the middle of the U-shape actuator. Due to the small size (the width of the actuator is only 70µm), it is hard to measure the temperature online. Our approach is to find the optimum annealing effect related to the laser annealing power from Differential Scanning Calorimetry (DSC) measurements.

A Si/Ge (Silicon Germanium) sensor is used to provide a feedback signal during the annealing and so to ensure a good repeatability of the process. Si/Ge sensor is a non-contact temperature sensor, which determines the temperature of an object by measuring the thermal radiation it emits.

The heating laser for annealing has a wavelength of 950nm. The diameter of the spot is about 1.5mm and the power distribution is nearly uniform within a diameter of 1mm. The heating process lasts for 1 second, which is proved to be long enough to have a well defined phase transformation (see DSC tests in the following part of this paper).

4. A precise screw is used to give the prestrain. As defined in the Section 2, the value of the prestrain is selected according to the stiffness of the actuator in low temperature martensite phase and high temperature austenite phase,
the stiffness of the bias spring that does not change with temperature, and the requirement of motion range. The maximum strain of the actuating spring should be larger than 2%, to induce the reorientation of martensitic variants during phase transformation, and less than 5% to ensure the required fatigue properties.

5. The gripper is fixed on a ceramic plate by glue and then freed from the remaining part.

6. Finally, the device is assembled on an aluminum holder and a PCB board is used to connect the gripper to an electrical current source (Fig. 6c).

4. EXPERIMENTS AND RESULTS

1. Differential Scanning Calorimetry (DSC) measurements

DSC is a common investigating method used to measure heat exchange during phase transformations in materials. As the martensitic phase transformation—which is the origin of the shape memory effect—is endothermal or exothermal depending on the material transforming from martensite to austenite or the reverse transformation, DSC is a very convenient tool to measure some characteristics such as the transformation temperatures. The results of these experiments are also used to compare to the effect of laser annealing to a conventional furnace annealing.

In order to investigate the effect of the laser annealing on the gripper, the actuating part of the gripper was cut by laser and put in a highly sensitive DSC experimental setup (the weight of a specimen is less than 0.25 mg).

In Fig. 7, key temperature points can be determined: $M_s$ is the temperature where martensite phase starts to form on cooling and $M_f$ is where martensite transformation finishes as well as the difference of $(M_s - M_f)$ marks the transformation duration from high temperature austenite phase to low temperature martensite phase. $A_s$ indicates the beginning of austenite transformation on heating and $A_f$ indicates the finish of austenite transformation and shape recovery, as well as $(A_f - A_s)$ identifies the duration of transformation from martensite to austenite. As mentioned before, due to the small size of our gripper, it is hard to measure the annealing temperature online. However, we may estimate the real annealing temperature by comparing with others’ measurements done on specimens of the same material furnace annealed in a given temperature.

Based on the DSC measurements, we observe that:

1. The reference sample (Fig. 7a) has a remaining transformation. However, the peaks are flat and not well defined. This remaining transformation is probably due to the low percentage of cold-rolling done by the manufacture. This phase transformation may be reduced or even removed by increasing the level of cold-rolling (for instance, up to 40 ~ 50%).
2. With the laser power increasing, the transformation peaks become narrow, sharp, higher, and well defined at 11W, then flatten and decrease with further increase of the laser power.
3. The transformation does not seem different if the annealing is performed several times or once. One second seems long enough for this annealing.
4. Multi-peaks are observed, which is related to the multiple transformations that may be as a consequence of the non-uniform heating condition during the annealing.

Fig. 8 gives the behavior of the transformation temperatures as a function of the laser power for annealing. Between 8 and 11W, there is a sharp increase of these temperatures. Therefore, by choosing the laser power, one can adjust slightly the transformation temperatures. Note that the transformation temperatures are also stress-dependent parameters and DSC measurements give the results under zero stress, i.e., the transformation temperatures are different under different loads [11].
2. Motion range
In our experiments, we have observed that the real stiffness of the bias spring is lower than expected: around one half to two third of the design calculation, and so does the maximum elastic strain, about 0.95 percent. One reason may lie in the slight annealing effect induced by the laser cutting to a long (2.3mm) and thin (85 µm) beam. Another reason might be the low level of cold-rolling done on the sheet. To take this effect into account, we measure the real stiffness of the
bias spring and estimate a mean value of Young’s modulus after cutting. The dimensions of the bias spring were modified according to this new value (as mentioned in Section 2).

The behavior of the gripper is measured by testing the motion range and time response of the moving finger. Measurements were performed using a high precision 3D-computer vision tracking system [12]. Fig. 10 shows the time response for a given triangle signal. We observed that a phase change could also occur in the bias spring for a given high level of current. Again, a possible explanation to this phenomenon may lie in the remaining phase transformation already mentioned before. Therefore, when the temperature goes higher, the bias spring undergoes a shape memory effect and reopens the fingers. Therefore, in Fig. 11a, the signal is modified to avoid the heating of the bias spring and so to keep the maximum closing position of the finger. The second highest current can be determined by the hysteresis effect shown on Fig. 9. Fig. 11b gives the corresponding time response to this signal. The maximum motion is lower than that on Fig. 10b.

![Triangle signal](image1.png)

**Fig. 10: Time response to a triangle signal**

![Modified signal](image2.png)

**Fig. 11: Time response to the modified signal**

5. CONCLUSIONS

We have developed a new parallel SMA microgripper that meets the critical requirements of 3D-assembly application for tissue engineering: large motion range and force, limited working space, temperature limitation (the melting point of our biodegradable material is about 100°C), simple control strategy and durability. A monolithic SMA micro-gripper was presented, which produces a guided motion thanks to an integrated parallel structure. This design principle bypasses size limitations of the laser cutting: objects smaller than the cutting groove can be grasped. The results also prove the feasibility and flexibility of local laser annealing. However, we observe that the actual stiffness and maximum elastic strain of the bias spring are lower than expected.
Further improvements will be done to reduce the remaining shape memory effect observed in the bias spring. One idea would be to increase the amount of cold-rolling and to reduce the effect of the laser cutting as much as possible. Another idea would be try another machining method like the EDM for instance.

Further experiments will be done to characterize this microgripper, in particular to measure the grasping force.

6. REFERENCES