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Ultrahigh vacuum (UHV) manipulators employ a variety of actuators, including mechanical, electrical motor, piezoelectric, pneumatic, and magnetic actuators. Shape-memory alloys (SMA), which were discovered[1] in 1963, have been somewhat overlooked,[2] although they are excellently suited to many manipulation needs. We present a simple design for an SMA-actuated manipulator, which can be machined entirely from stainless steel, except for one ceramic tube and the commercially available SMA wire. We have used this manipulator down to 1×10^{-10} Torr.

In the conventional shape-memory effect,[3] the piece of SMA is set to a desired shape, then heated above annealing temperature to cause "memorization." While above the annealing temperature, the piece is in the austenitic phase. Upon cooling, it reverts to the martensitic phase, which contains many twin boundaries. While cool, the piece can be deformed by an external force relatively easily, within limits allowed by the shifting of twin boundaries, and yet will return to the memorized austenitic phase and shape upon heating to a transition temperature, which is lower than the annealing temperature. The deformation/return cycle can be repeated numerous times, so long as the piece is kept below the annealing temperature.

In the two-way shape memory effect,[4] the alloy piece "remembers" both a high temperature and a low temperature shape, so that no external deformation force is required. This effect is accomplished by "training" the alloy through repeated cycles of externally-enforced deformation, sometimes while heating. The training apparently produces a network of local defects which favors the formation of a particular twinning pattern.

We use a commercial NiTi SMA wire,[5] which is particularly convenient because it is pretreated to exhibit a partial two-way effect; it is trained to a short high temperature length, and to a longer low temperature length. The extent of recovery to the low-temperature shape is limited; the main effect of the training is to lessen the amount of external force required to stretch the wire as it cools. Heating the wire to 115 °C by passing a current through it causes it to shorten, by up to 5%, pulling with a force of up to 2×10^8 N/m^2 (or 3.5 N for the 150 μm-diam wire we used). Upon cooling, it is re-extended by a spring in the manipulator. The composition of the wire is fully UHV compatible.

Figure 1 shows a diagram of the manipulator head, which is designed to grip $0.25\times0.25\times0.02$ in. silicon chips. The SMA is used to open and close the jaws. The manipulator head is attached to a commercial magnetically coupled manipulator shaft[6] which provides longitudinal and rotational motion; a gimballed bellows mount for this shaft allows approximately 20 cm of side-to-side and up-and-down motion. The complete separation of the ja opening from the other degrees of freedom, and the ele trical control allow for precise and delicate grabbing.

The heating current is provided by a 22 gauge (0.6 m diam) copper wire insulated with fiberglass sleeving which is coiled around the manipulator shaft, and stres relieved at a screw on the manipulator head, as shown. T

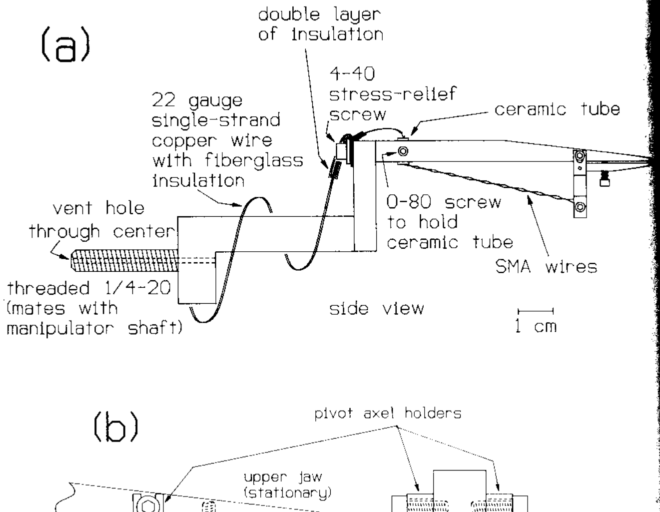
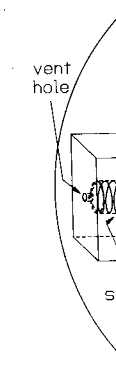


FIG. 1. (a) Schematic diagram of manipulator head. All dead-end screw holes are vented,either with small vent holes or with center-drilled screws. (b) Close-up of jaw mechanism. The spring-retaining screw is also used for spring tension adjustment. The threads near the head of this screw are sanded down, to allow smooth motion of the jaw. The spring is 3/8 in. long, 1/8 in. outer diam, and is made of 0.018 in stainless wire (PIC Design, Middlebury, CT). (c) Close-up of jaw tips holding a sample.



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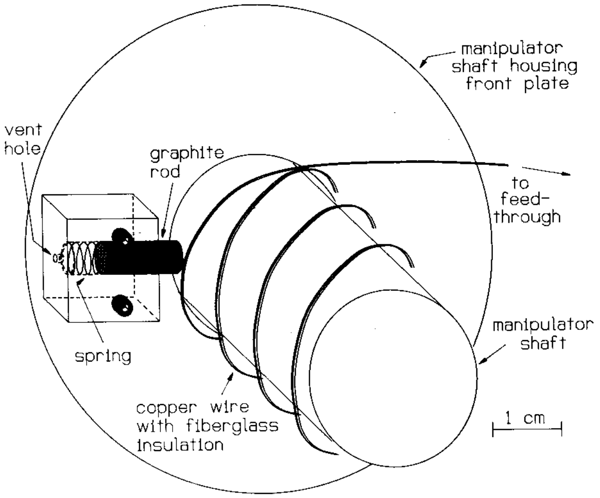

FIG. 2. Schematic diagram of spring-loaded graphite ride which rides on manipulator shaft, preventing the wire from jamming the shaft motion.

avoid shorts, we use double fiberglass sleeves at the stress-relief screw. The other end of the copper wire is attached to a conventional electrical feedthrough. To prevent the coil from tangling, it is essential to use relatively heavy-gauge wire. Also, to keep the wire from jamming the manipulator shaft as it is pulled back, we have installed a spring-loaded graphite rod which rides on the shaft at the housing entry, as shown in Fig. 2. Since our shaft rides on Teflon bearings, the graphite rod is also needed to ensure a reliable ground. This coil set-up is extremely reliable, and has never tangled. Of course, the coil prevents unlimited rotation; however, the manipulator can be rotated several turns in either direction without any problem.

To allow for a stronger spring (and thus a firmer grip), we use four SMA wires, braided together. Each SMA wire is simply tied around the copper wire with a single overhand knot; the SMA wire is stiff enough to keep the knot from pulling out. The knot provides a reliable electrical contact. The SMA wires then pass through the ceramic tube. The other end of each wire is grounded by being clamped to the lever arm of the jaw.

When current is applied, the SMA wires pull on the lever arm, opening the jaw by up to about 2 mm. By adjusting the heating current, the degree of opening can be continuously controlled. In vacuum, approximately 210 mA is required to fully open the jaws, and about 750 mA in air. (Recall that this current is split between the four braided SMA wires.) If the current is taken too high (to approximately 230 mA in vacuum), the annealing temperature will be exceeded; the SMA wires will become slack, and lose their pulling force.

The spring, which provides the gripping force when the wires are cool, has a spring constant of 2.6 N/mm. We have adjusted the tension screw so that, when the jaw is closed, the spring is compressed by about 2.5 mm, providing about 2 N of gripping force at the jaw tips. To fully open the jaws (2 mm spacing between jaw tips) requires 1.4 N from each of the four SMA wires.

Originally, we found that,even when the sample held in the jaws was gripped firmly, it was still liable to rotate when we tried to insert it into other holders in the vacuum system. This problem was due to the smoothness of the sample and jaw surfaces. (A smooth jaw surface is desirable to avoid undue marring of the sample.) So, we added small steps to the jaw tips, as shown in Fig. 1(c). With this modification, the sample is held securely against rotation.

Acknowledgment: The authors are grateful to Darel Hodgson for discussions on details of "BioMetal" manufacture and application.

[1] W. J. Buehler, J. V. Gilfrich, and R. C. Wiley, J. Appl. Phys. **34**, 1475 (1963).

[2] The reported uses of SMA for motion in vacuum are as follows: B. J. Mulder, Vacuum **26**, 31 (1975) (Prototype coil design, used only for testing of the SMA.); E. F. Yamschkov, Instrum. Exp. Tech. **21**, 1422 (1978) [Pribory i Tekhnika Eksperimenta **21**, 241 (1978)] (Design using a bent plate which straightened when heated, used for actuating a valve.); A. P. Jardine, M. Ahmad, R. J. McClelland, and J. M. Blakely, J. Vac. Sci. Technol. A **6**, 3017 (1988) (Coil design for moving a shutter.); M. E. Shcherbina, Instrum. Exp. Tech. **32**, 507 (1989) [Pribory i Tekhnika Eksperimenta **21**, 221 (1989)] (Very complex sample exchange mechanism using SMA rods.); K. Obara, K. Nakamura, Y. Murakami, M. Obama, and M. Kondoh, Fus. Eng. Design **10**, 495 (1989) (Manipulator arm using SMA wire for use in fusion reactors.); M. Nishikawa, M. Kawai, T. Yokoyama, T. Hoshiya, M. Naganuma, M. Kondo, K. Yoshikawa, and K. Watanabe, J. Nucl. Mater. **179-181**, 1115 (1991), and references to the same apparatus therein. (Large gate valve using SMA tubes for use in fusion reactor.)

[3] See, for example, *Shape Memory Effects in Alloys*, edited by J. Perkins (Plenum, New York, 1975); or T. W. Duerig and K. N. Melton, Proc. Mater. Res. Soc. Int'l. Mtg on Adv. Mats. **9**, 581 (1989).

[4] See, for example, J. Perkins, Mater. Sci. Eng. **51**, 181 (1981).

[5] 6-mil "BioMetal" wire, obtained from Mondo-tronics, Inc., San Leandro, CA.

[6] Vacuum Generators, Ltd., Hastings, England.

[7] Electrical Insulation Suppliers, Inc., Garland, TX.