J. PHYS. IV FRANCE 7 (1997)
Colloque C5, Supplément au Journal de Physique III de novembre 1997

Grippers for the Micro Assembly Containing Shape Memory Actuators and Sensors

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Abstract. Shape memory alloys (SMA) show a high ratio of work capacity per material volume. This makes the application of SMA especially useful in micron-sized systems. The development of robotic grippers is one important prerequisite for the successful automation of the assembly of micro systems. Therefore the SMA may also play a role, for example, as actuators in micron-sized grippers.

This paper presents the development of micron-sized grippers. Due to a special relation between the electrical resistance and the shape change of a NiTi-wire the actuator may also be used simultaneously as a sensor. Besides these functional properties a superelastic SMA may be used for structural purposes, i.e. as solid-state flexure hinges.

The sensoric features of binary and ternary NiTi-based alloys are investigated using different $Ti_{50}Ni_{50-x}Cu_x$ alloys with $0 < x < 25$ at-%. Besides the chemical composition the functional properties are affected by the thermo-mechanical treatment (TMT). Different TMT of $Ti_{50}Ni_{50-x}Cu_x$ alloys and their influence on the functional properties are compared. The effect of the TMT on the amount and the stability of the shape memory effect has to be taken into account if the optimum alloy and condition for the use in grippers for micro assembly are investigated.

The function and the properties of the developped gripping devices are demonstrated by prototypes.

1. INTRODUCTION

In comparison to other actuator materials shape memory alloys (SMA) offer a substantially higher work output per material volume. This makes the application of SMA actuators especially useful in systems, where miniature actuators are necessary. Therefore the increasing field of microsystems is a potential future market for shape memory alloy based actuators. These microsystems may be fabricated monolithically, like for example micro-chips. Particularly if a small-lot production is planned the monolithical fabrication is much too expensive, so that nowadays it seems to be more probable, that most of the future microsystems will be produced as hybrids, which have to be assembled from a number of single parts. The feasibility of such hybrid microsystems depends also on the availability of adequate assembly devices. Besides the necessary high precision robot there is a substantial need for suitable grippers. Those have to fulfill a number of requirements, which are typical for the micro-assembly:

- the assembly has to be carried out under clean room conditions, where robots and grippers are potential sources of pollution and have to be encapsulated in order to prevent pollution caused by joints or gears,
- the gripper should be very small and lightweight in order to minimize the total weight, which has to be handled by the robot. This leads to smaller and more lightweight robots, which are less expensive, more precise (e.g. due to less thermal expansion) and which require less of the expensive clean room space,
- the gripper needs integrated sensors for the gripping force as well as for the size of the gripping object,
- the electronic control of the gripping process is important and
- the amount and the stability of the gripping force has to be maximum in order to achieve minimum energy consumption of the actuator material.

Besides these requirements there are a number of other difficulties which are specific for a gripper for micro-assembly if the size of the gripping object is reduced significantly below 1 mm. One major aspect is the behaviour of the gripping objects which changes with decreasing dimensions. For conventional assembly processes the grippers are designed with respect to the weight of the gripping objects, so that the available gripping force exceeds the weight of the object including the acceleration force during handling. If the gripper opens the object is released immediately. With progress in reduction of the size of the object the electrostatic force between the object and the gripping claws increases in relation to the weight and can not be neglected any longer. Whereas the weight is proportional to the volume, the electrostatic forces are proportional to the gripping object's surface. As a consequence the opening of the gripping jaws is not necessarily related to the immediate release of the object. It is obvious that the relation of surface versus volume and therefore the electrostatic interactions increase with further progress in microsystems. These problems with electrostatic interactions may be overcome by using electrically conductive and grounded gripping jaws which reduce the differences in electrostatic potentials.

2. DEVELOPED MINIATURE GRIPPERS

All of the above mentioned requirements are fulfilled by recently developed mechanical micro-grippers shown in **Fig. 1** and **2**. In comparison to other gripping principles mechanical grippers are advantageous in the following aspects:

- flexibility of design and exchangeability of the gripping jaws in order to meet nearly every gripping task (difference in size, shape or weight of the object),
- robust construction,
- automatic centering of the object.

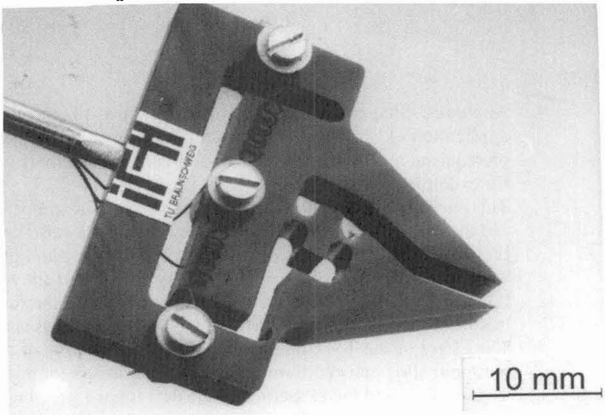

Fig. 1: Prototype of a miniature gripper for micro assembly using two helical springs in a differential actuator design [1].

The presented grippers contain actuators made of NiTi-based shape memory alloys. The structures of the grippers are fabricated from one single part with well defined elastic regions, the so called flexure hinges. They are made of either thermoplastic polymers (e.g. POM) or pseudoelastic shape memory alloys by locally reducing the stiffness of the material. In contrast to conventional gripping mechanisms the used flexure hinges work without any bearings or lubricants. Similar to the actuator the structure does not release any particles. The mechanisms achieve a high flexibilty concerning design and mobility by using the extraordinary compliance of the structure.

The gripping mechanism shown in **Fig. 1** uses two helical springs in a differential-type actuator design (agonist - antagonist actuators). The structural component of the gripper in **Fig. 1** is highly flexible and does not store any elastic deformation energy. The differential actuator design offers significant advantages concerning the response characteristic of the gripper: after the handling of the gripping object the releasing is enhanced by heating the antagonist actuator which causes the agonist actuator to deform instantly. The reason for this deformation is the appearance of a stress induced transformation which in contrast to a thermally induced transformation does not need extra cooling time.

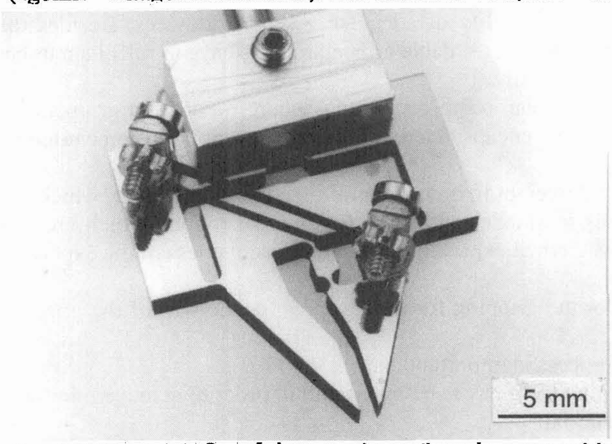

Fig. 2: Prototype of a miniature gripper for micro assembly using NiTiCu ribbon (alloy B25, **Tab. 1**) as an actuator and as a sensor simultaneously [1].

The gripper presented in **Fig. 2** uses a structural component made of pseudoelastic NiTi which is machined by EDM. The pseudoelastic structure is able to store the elastic deformation energy which is necessary for the appearance of the two-way effect (TWE). The actuator is made of a melt-spun NiTiCu-ribbon (alloy B25, see **Tab. 1**) with an excellent relation between surface and volume (cross section of 2 x 0.035 mm^2). One major advantage of this gripper is the robustness which is due to the massive metallic structure. On the other hand this gripper shows a slower response characteristic in comparison to the gripper presented in **Fig. 1** which is mainly due to the different actuator design.

This gripper uses the SMA-ribbon as an actuator and simultaneously as a sensor ("Smart Material"). For this the use of a special relationship between the electrical resistance and the shape change of the element is a necessary prerequisite. From former work [1-5] it is well known, that some special alloys show a linear and hysteresis-free relationship (**"Ω-characteristic curve"**, **Fig. 3**) which is especially useful for control purposes because it allows the direct integration of the actuator in a closed loop control circuit. **Fig. 3b** shows this relation for two different materials, with material I offering good and material II showing quite poor control properties. From this it can be seen that better control properties of an actuator are related to:

- a small width of the hysteresis (H≈1%, **Fig. 3b**) in the Ω-characteristic,
- linear appearance of the Ω-characteristic,
- large amount of shape change of the actuator.

The width of the hysteresis is of particular importance because it is directly related to the precision of the position control: the smaller the amount of H, the higher is the quality of the position control in the closed loop mode.

The subject of this paper is to investigate and optimize different NiTi-based shape memory allloys for the use in micron-sized gripping devices. Besides the available shape change the electrical resistivity characteristic is of particular interest. The thermomechanical treatment (TMT) of four different $Ti_{50}Ni_{50-x}Cu_x$ alloys (Cu between 0 and 25 at.-%) is optimized with respect to the above mentioned requirements. The functionality of the grippers is shown in prototypes.

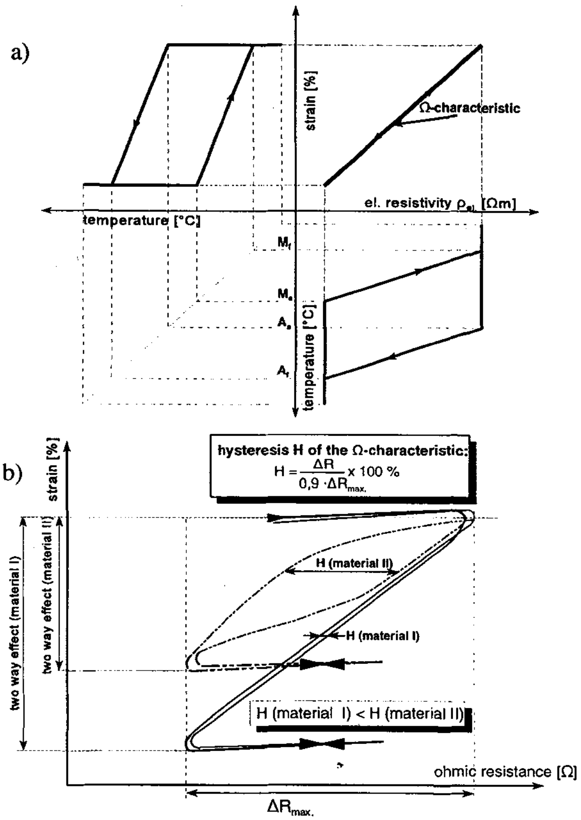

Fig. 3: Relationship between the electrical resistance and the shape change (strain) of a straight NiTi actuator wire (**"Ω-characteristic curve"**). The Ω-characteristic is a superposition of two different relations, both of them showing a distinct hysteresis (a). Certain NiTi-based actuators offer this unique control property due to their small width of the resistance hysteresis (b).

3. OPTIMIZATION OF THE Ω-CHARACTERISTIC

3.1 Experimental

Four different NiTi-based alloys are investigated in this study (**Tab. 1**). All specimen are prepared by cold drawing to wire, except the meltspun ribbon from alloy B25, which are examined after annealing at 500 °C/5". The amount of cold work achieved with the last drawing die is between $\varphi_1 = 15$ % and $\varphi_2 = 34$ % reduction in area. The wire drawing is followed by a defined thermal treatment, the parameters of which are:

350 °C < T < 600 °C, t = 900 sec. An annealing time of more than 900 sec. has shown to be ineffective for the further improvement of the Ω-characteristic, so that all tests are carried out with a 900 sec. heat treatment. The phase transformation temperatures are measured without external load in a Differential Scanning Calorimeter (DuPont Thermal Analyser 2100) with a heating rate of 10 K/min. The measurements of the Ω-characteristic are carried out in a special testbed [1]. For this investigation 500 mm of each specimen are fixed in the testbed and a constant load σ = 50, 100 or 150 MPa is applied. The shape change occurs when the wires are heated by a computer controlled source of current so that the load is lifted. The ohmic resistance of the actuator is calculated and stored by a computer from the applied current and the measured voltage as a function of the wire contraction caused by the phase transformation. The wire strain is measured by an inductive displacement transducer.

Alloy	Ni [at.-%]	Ti [at.-%]	Cu [at.-%]	fabrication
BO	49.6	50.4	0	cold drawn, d = 0.38mm
X2	45.0	50.0	5.0	cold drawn, d = 0.38mm
G4	40.6	50.3	9.1	cold drawn, d = 0.38mm
B25	25.0	50.0	25.0	meltspun, 2 x 0.035mm^2

Tab. 1: Composition, fabrication and dimensions of the four different alloys used in this study.

3.2 Results and Discussion

The Ω-characteristic curve can be understood as the superposition of the relation between

- the apparent strain and
- the electrical resistivity

as a function of temperature during the phase transformation. Both mechanisms depend on the volume fraction of martensite to austenite. Therefore the volume fraction during the transformation can be regarded as the basic mechanism behind the Ω-characteristic. All factors affecting the volume fraction of the balance between the two phases should therefore have an effect on the appearance of the Ω-characteristic.

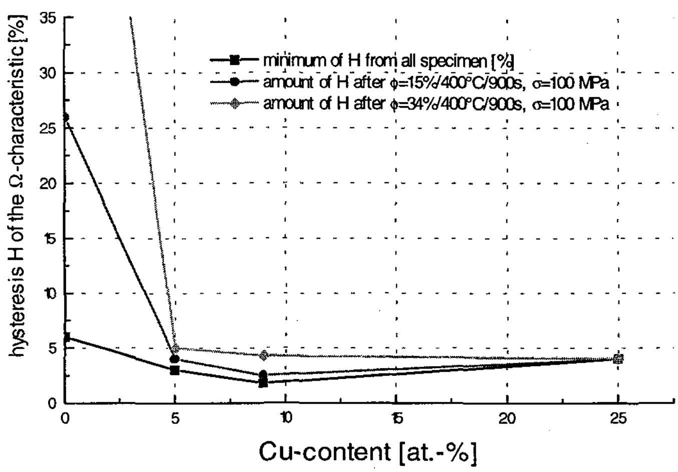

Fig. 4: Effect of the Cu-content and the cold work on the amount of hysteresis H in the Ω-characteristic.

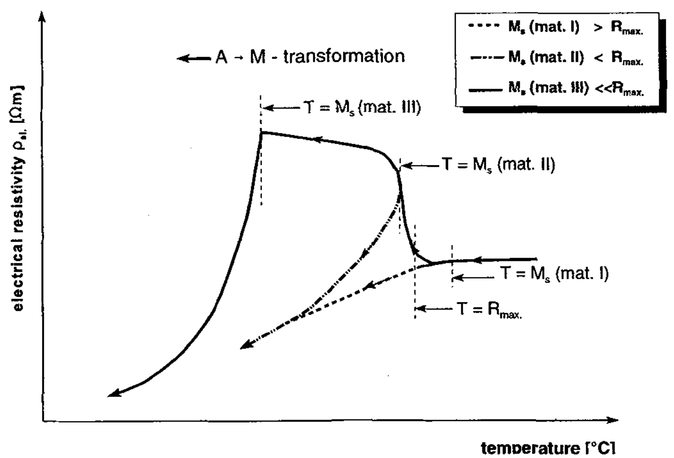

Fig. 5: The electrical resistivity of a binary NiTi alloy depends on the difference between the R and the M transformation temperatures. An increasing difference leads to a more pronounced anomaly of the specific resistivity [6].

As a main result it is found out that the amount of hysteresis of the Ω-characteristic depends strongly on the chemical composition of the material and on the thermomechanical treatment of the wire (**Fig. 4**). Furthermore the applied load during the transformation cycle affects the result. Smaller amounts of H are achieved by adding substantial amounts of Cu. The optimum Cu content seems to be around 10 at-% Cu, whereas hig-

her as well as smaller amounts are also benefical for the width of resistance hysteresis.
In contrast to the alloy BO, the resistance characteristic of the Cu-containing alloys X2 and in particular of alloy G4 are much less sensitive to TMT. The reason for the decreasing width of hysteresis is mainly the absence of a premartensitic R-phase transformation in NiTiCu-alloys. The R-phase appears in binary Ni-rich as well as Ti-rich alloys and is combined with a distinct anomaly of the electrical resistivity [6]. In the Ti-rich alloy BO the R-phase transformation (B2 → R) is found in a DSC measurement with peak seperated from the M-phase transformation (R → B19') during cooling. The difference between the two peak temperatures $M_{max.}$ and $R_{max.}$ increases with decreasing heat treatment temperature after a substantial amount of cold deformation of at least $\varphi > 20$ %. Obviously the reverse transformation in these alloys takes place at the same temperature so that the M→R and the R→B2 reverse transformation peaks cannot be seperated in a DSC-cycle. The resistance anomaly becomes even more distinct the more the difference between the R-phase and the M-phase transformation temperatures increases (**Fig. 5**). As a consequence of this the R-phase transformation in a binary NiTi-alloy should be avoided by a thermomechanical treatment:

- higher annealing temperatures: $T \geq 500$ °C or
- less cold work: $\varphi \leq 15$ %

if the Ω-characteristic has to be used for control purposes.
Depending on the Cu-content the transformation sequence changes in the ternary NiTiCu-alloys. These materials transform either with the sequence

B2→B19 (orthorhombic)→B19'

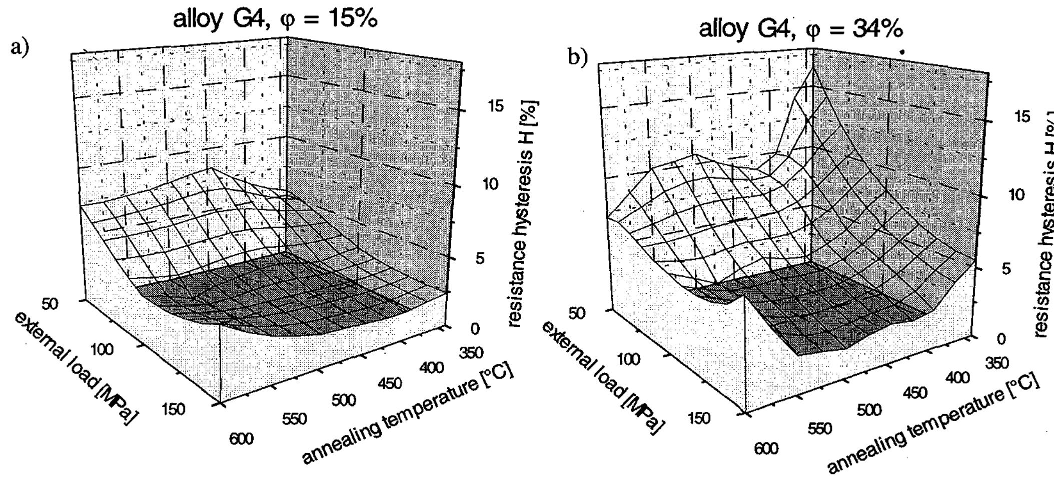

Fig. 6: Influence of the external load (a), of the amount of cold work (b) and of the annealing temperature on the Ω-characteristic of alloy G4. Higher loads and intermediate annealing temperatures lead to decreasing amounts of H and therefore to better control properties.

or with

B2 → B19'.

The sequence depends on the Cu-content. Alloys with more than about 8 at.-% Cu (e.g. alloy G4) show the former transformation sequence, whereas alloys with less than 7.5 at.-% Cu (e.g. alloy X2) transform according to the later sequence respectively [7,8]. The R-phase transformation is not observed. This is the main reason for the decreasing width of hystersesis in the Ω-characteristic of the ternary alloys, especially if the technologically relevant annealing temperatures of less than 500 °C (350 °C < T < 450 °C) are applied. Furthermore it becomes evident that the amount of cold deformation is less important for most of the functional properties in a Cu-containing material in comparison to the binary alloys.
The reason for the decreasing width of hysteresis with increasing external load on the one hand and annealing temperatures of 400 to 450 °C on the other hand is the increasing amount of shape change which has a significant effect on the characteristic curve of the electrical resistance. This is due to a higher amount of maximum actuator strain whereas the difference between the resistivity of the martensite and the austenite

is not affected by the shape change. Therefore the hystersis for the material with the minimum shape change is widened (see **Fig. 3b**, material II).
From the above mentioned it can be assumed that the width of the hysteresis of the Ω-characteristic for one material with given chemical composition depends strongly on phase transformation temperatures. Those are determined by the thermomechanical treatment and by the applied external load and have to be adjusted in a way that the appearance of the Ω-characteristic becomes linear and hysteresis-free. This allows the application of a closed loop position control in which the shape memory actuator works as actuator and sensor simultaneously.

4. CONCLUSIONS

The development of miniature robotic grippers with integrated multifunctional (actuator and sensor) NiTi-based elements is described. The use of flexure hinges has proved to be suitable for the application in such grippers. One of the presented prototypes uses the SMA in a triple function: besides the actuator and the sensor function the structure is fabricated from pseudoelastic SMA so that the gripper is very robust.
The second topic of this paper is the optimization of the Ω-characteristic by adding about 9 - 10 at.-% Cu to the alloy. This leads to improved control properties of NiTi actuators, because the hysteresis of the resistance vs. shape change characteristic is reduced. This is mainly due to the absence of a premartensitic R-phase transformation in the NiTiCu alloys. Furthermore the amount of hysteresis may be reduced by an optimum thermomechanical treatment which consists of a cold work of 15 % and subsequent annealing at temperatures between 350 and 450 °C. The applied load should be about 80 - 120 MPa during the transformation cycle.

Acknowledgements

We gratefully acknowledge the financial support of our work by the German Science Foundation (DFG Ho 325/30-2) and the Volkswagen Stiftung (I/70283).

Literature

[1] J. Hesselbach, R. Pittschellis, H. Storck, M. Mertmann, E. Hornbogen: Optimization and Control of Electrically Heated Shape Memory Actuators; Proc. 4th Int. Conf. on New Actuators, ACTUATOR 94, 15 - 17 June 1994, Bremen, Germany, 337 - 340.
[2] D. Reynaerts. J. Peirs, H. Van Brussel: Production of Shape Memory Alloys for Microactuation; J. Micromech. Microeng. 5 (1995), 150 - 152.
[3] A. Pruski, H. Kihl: Shape Memory Alloy Hysteresis; Sensors and Actuators A, 36 (1993), 29 - 35.
[4] G. Airoldi, T. Ranucci, G. Riva: Electrical Resistance as a Function of Deformation in Shape Memory Alloys, Trans. Mat. Res. Soc. Jpn., 18B (1994), 1109 - 1112.
[5] G. Airoldi, T. Ranucci, G. Riva: Mechanical and Electrical Properties of a NiTi Shape Memory Alloy; Journal de Physique IV, Coll. C4, Vol. 1 (1991), C4-439 - 444.
[6] H.C. Ling, R. Kaplow: Phase Transitions and Shape Memory in NiTi; Met. Trans 11A (1980), 77-83.
[7] S. Miyazaki, S. Chujo: Effect of Cu Addition on the Two-Way Shape Memory Effect in Ni-Ti alloy; Proc. 1st. Int. Conf. on Shape Memory and Superelastic Technologies SMST94, Monterey, CA, USA (1994), 73 - 77.
[8] G. Airoldi, T. Ranucci, G. Riva, A. Sciacca: The Two-Way Memory Effect in a 50 at.-% Ti- 40 at.-% Ni-10 at.-% Cu Alloy; J. Phys.: Condens. Matter 7 (1995), 3709 - 3720.