Thermomechanical Characterization and Medical Application of NiTi Shape Memory Alloys

M. Thier, Institut für Werkstoffe, Ruhr-Universität Bochum, D-4630 Bochum

Introduction

The thermomechanical behaviour of the so called shape memory alloys has become well known due to its pseudoelastic properties and the shape memory effect.

The most important alloy in industrial and medical application is the intermetallic compound NiTi. The increasing interest in this alloy is founded in a rubber-like behaviour associated with a wide working range; also it has a lower modulus of stiffness than stainless steel and the ability to rearrange an impressed shape, after deformation, only by the use of external heat.

NiTi alloy has a good resistance to corrosion. According to the medical application of NiTi several authors have found that it is of sufficient biocompatibility (1,2). So a great number of medical applications from external devices to temporary and permanent implants have been suggested. Some of them have been tested and become successful in medical use today (3,4).

A precise temperature or temperature range has to be adjusted to activate the thermomechanical behaviour of a shape memory alloy. For medical devices the use of the body temperature is one means of doing this. The vena cava filter using the one-way shape memory effect is an obvious example. However, this is not always possible. A higher activation temperature than the body temperature with the use of external heat is needed for several devices. The advantage is that by a controlled application of heat a precise activation up to a required degree can be reached. So gradual heating should be preferred when a damage of the biological structure must be taken into consideration. In order to realize a controlled application of heat one needs a flow of sterile water, a contact to a heat element or the resistance heating of the medical device.

The purpose of this paper is to discuss the variety of the application of thermomechanical behaviour of NiTi shape memory alloy as medical devices. First experiments to examine the thermomechanical characteristics of the NiTi alloy in Ti-49.0 at.% Ni, Ti-49.9 at.% Ni and Ti-51.0 at.% Ni composition are reported.

Medical devices

The thermomechanical characteristics of NiTi alloy lead to several devices of medical application. The pseudoelastic properties as well as the shape memory effect are used for new development in surgical instrumentation, external application and implantology.

During surgical treatment it is difficult to tell the healthy tissue from the tumour. Only radiological observation makes such a diseased tissue visible. Therefore a pseudoelastic wire with an impressed hook at the top is placed in a tube (Fig. 1). During radiological control the tube is brought to the tumour, the pseudoelastic wire is pushed out and the diseased tissue is enclosed by the impressed hook at the top of the wire. The tumour is now marked and can be removed by surgical means (5). The pseudoelastic characteristics of NiTi alloy, in this application used at body temperature, help the surgeons to localize a diseased tissue during surgical removal.

In dental treatment the correction of tooth position requires a low level power that remains constant in a wide range. These demands are insufficiently fulfilled by the use of a stainless steel wire. A new orthodontic wire, made of NiTi alloy, makes this job possible. The Young's modulus of the NiTi alloy is about 25 % of that from stainless steel. This results in an efficient reduction of the applied forces. The pseudoelastic properties, here again used at body temperature, place a wide range of action to the dentist's disposal. The external application of orthodontic NiTi wire gives new means of correction treatment to the dentists (6,7). So the applied forces can accommodate biomechanical conditions and the greater working range should lead to less adjustments and shorter treatment time.

Fig. 1: Pseudoelastic NiTi wire used for marking a tumour (5)

A good compression of the resection surface is needed in surgical correction of joint axis. For example in the osteotomy of the head of the tibia: after the resection of the correction–wedge the osteotomy is fixed by osteosynthesis clips and compression is applied on the resection surface (Fig. 2).

Fig. 2: X–ray picture showing an osteotomy of the tibia head fixed with two memory clips; eight weeks after surgical intervention (4)

The clips are made of NiTi alloy and their memory will be activated just above body temperature. The clips are stretched and driven into the bone by a hammer. The one–way shape memory effect is used here and is obvious that an activation, i. e. a compression of the osteotomy gap, should occur when the memory clips are fixed in the bone. After fixation they are activated by a controlled application of resistance heating (4). Temporary implants like NiTi memory clips enable the surgeons not only to fix bone after fracture or osteotomy but even a good compression promoting the healing process and applied in a controlled manner can be achieved.

Blood clots mainly formed in legs, thighs or pelvis lead to pulmonary embolism. A blood clot filter, implanted in the vena cava, is one possibility to prevent blood clots from reaching the heart– or lung region. The surgical procedure, necessary to place the filter into the vena cava, involves some risk. An NiTi memory alloy is used to place a filter into the vena cava without a surgical intervention (8). Therefore, a filter shaped NiTi wire is straightened. As far as reaching the vena cava a catheder is brought into the venous system. The straightened NiTi wire, while being cooled in a solution, is pushed through the catheder. As soon as it reaches the vena cava the wire leaves the catheder. It is warmed up by the blood and moves back to its impressed filter configuration (Fig. 3).

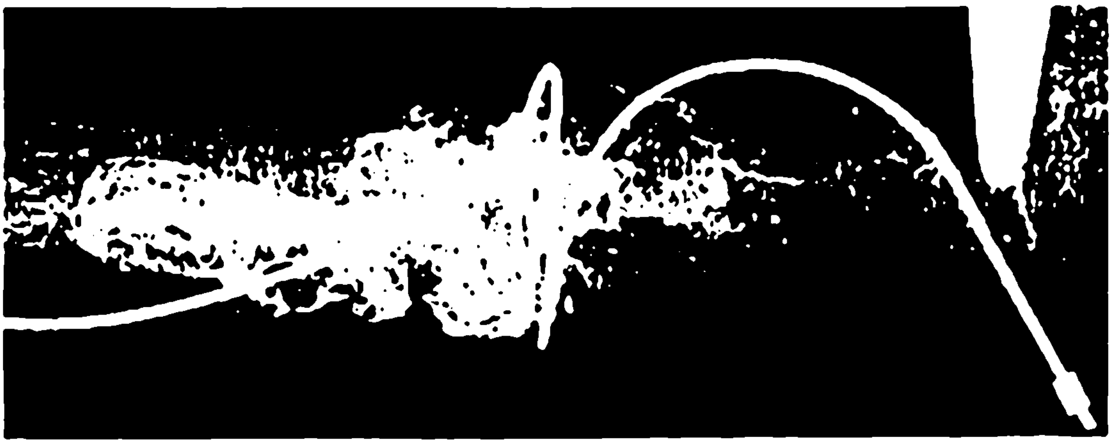

Fig. 3: X–ray picture showing an NiTi filter placed in a dogs vena cava (8)

The vena cava filter is an example of a permanent implant made of NiTi alloy. In this application the body temperature is used to activate a one–way shape memory effect. Without a surgical intervention a complex filter is brought into the venous system only by the use of the blood temperature and the thermomechanical characteristics of NiTi alloy.

A wide area of possible applications will be opened by a new heating apparatus. Already implanted devices can be manipulated by the use of high frequency induction (9). Corrective working or other interventions will now be possible even up to five or ten years after the original surgical treatment.

Medical devices such as surgical instruments, external applications, temporary and permanent implants make use of the thermomechanical characteristics of NiTi alloy. The pseudoelastic properties as well as the shape memory behaviour help the surgeons in different applications. The temperature or temperature range that has to be adjusted depends on the specific demands of that what is intended to be realized or at least to be improved. The heating up can be done by the body temperature but only an activation temperature chosen higher than the body temperature gives sufficient means of control to the surgeons. The variety of applications discussed here and that what seems to be possible should lead to a great number of medical devices using the thermomechanical characteristics of the shape memory alloys.

Thermomechanical characteristics

The application of a shape memory alloy involves a complete knowledge of its mechanical and thermal behaviour. Forces and elongations realized by a reversible phase transformation have to be studied in mechanical as well as in thermal hysteresis.

For the exploring of the thermal hysteresis the constrained mode– and the constant load mode experiment have become well known. In this paper the results of a constant load mode experiment in Ti–49.0 at.% Ni, Ti–49.9 at.% Ni and Ti–51.0 at.% Ni, solution treated at 1000 °C for 1 h and aged at 600 °C for 1 h, will be discussed.

The specimen is placed in a heating/cooling equipment and a constant load is applied (Fig. 4). The temperature range of phase transformation is driven through while temperature versus strain is recorded.

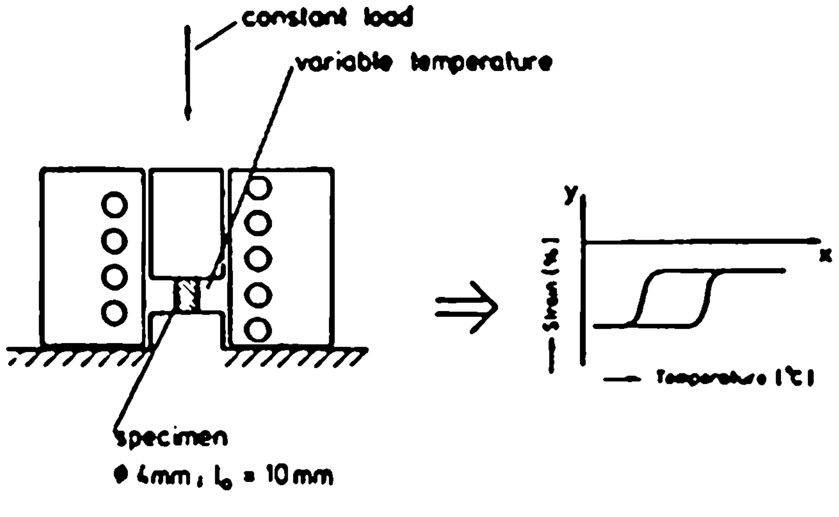

Fig. 4: Experimental design of the thermal hysteresis experiment carried out in the constant load mode

A typical elongation versus temperature hysteresis is shown in Fig. 5. Loading the specimen in the high temperature phase instead of loading in the low temperature phase leads to some remarkable observations.

The transformation to the low temperature phase occurs at a higher temperature under the application of load. A "loaded" transformation into the low temperature phase produces greater values of strain than subsequent loading in the low temperature state. The transformation into the high temperature phase is complete for a loading of 260 MPa. Only the specimen loaded in the low temperature phase shows some unsteadiness in the rebuilding of the high temperature phase.

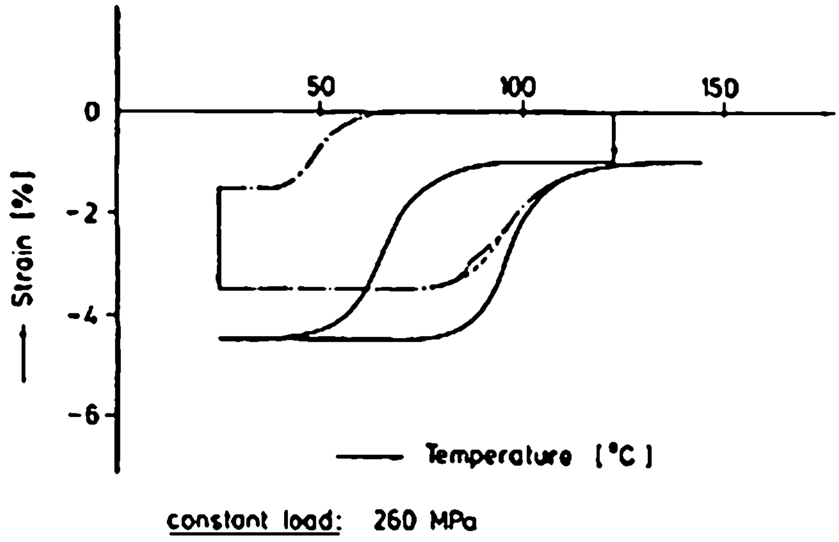

Fig. 5: Transformation hysteresis of Ti–51.0 at.% Ni load in the high temperature phase (———) and loaded in the low temperature phase (· — · — · — · —)

Raising the constant load to higher stresses (Fig.6) the transformation hysteresis is left incomplete and the re–transformation into the high temperature phase seems to become stepwise (10).

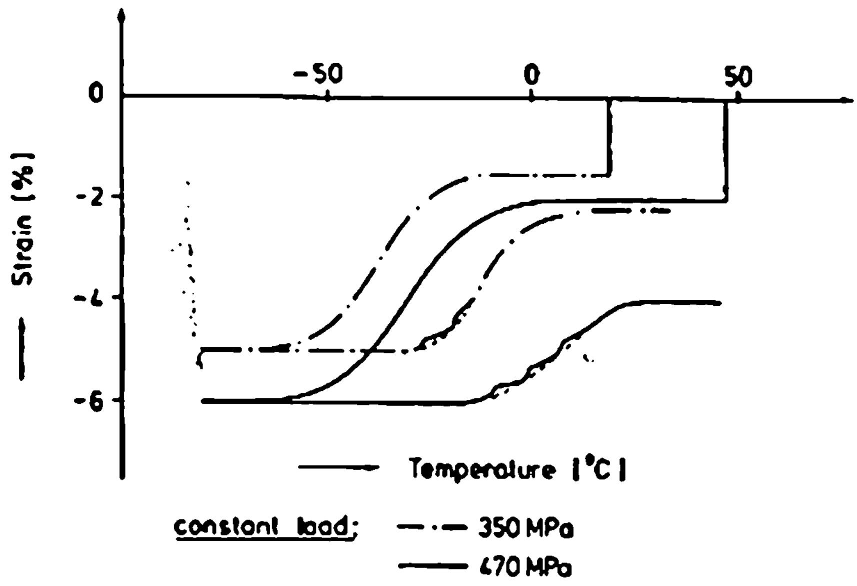

Fig. 6: Influence of further raising of stress on the transformation hysteresis of Ti–51 at.% Ni

The thermomechanical characteristics of the NiTi memory alloy lead to the ability that these alloys can do mechanical work (Fig.7).

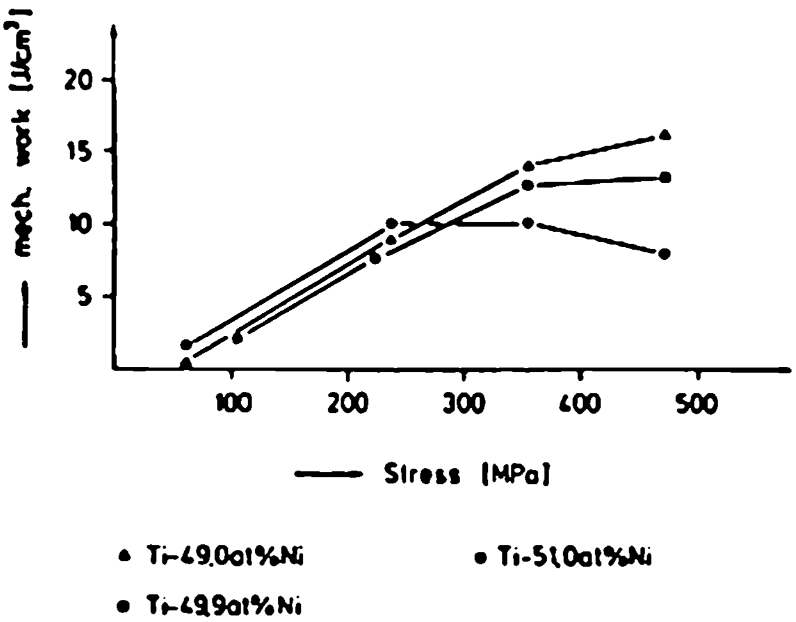

Fig. 7: Mechanical work of NiTi alloy in three alloys containing 49.0, 49.9 and 51.0 at.% Ni

According to the alloy composition they show a different behaviour when higher stresses are applied. Reaching about 200 MPa a linear increase of the mechanical work can be seen for all the alloy compositions. Further raising of the applied stress leads to an enormous decrease in mechanical work of the Ti–51.0 at.% Ni alloy. The alloys with the composition of Ti–49.9 at.% Ni and Ti–49.0 at.% Ni show an even slighter decrease in mechanical work at stresses of about 350 MPa.

In medical application of NiTi memory alloy the activation temperature of the device has to be well chosen in consideration of the medical circumstances. Both the use of the body temperature as well as an external application of heat can be possible to establish the right temperature or temperature range of activation. To study the thermomechanical characteristics of the shape memory alloys, results of a first experiment in the so called constant load mode are presented. Further investigations to improve the thermomechanical abilities of the NiTi alloy as a medical device will be undertaken.

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