19th International Conference on
Adaptive Structures and Technologies
October 6-9, 2008
Ascona, Switzerland

On the damping capability of NiTi based thermoelastic martensite

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ABSTRACT

Nickel Titanium based shape memory alloys (SMA) show features which are not present in traditionally engineering materials: The thermal shape memory effect and superelasticity. In addition, shape memory alloys exhibit very good damping capabilities, which have made them attractive for either active or passive usage in vibration suppression devices. This paper focuses on the passive damping capability, which is based on moveable phase interfaces and variants within the microstructure of SMA materials in their martensitic phase (thermoelastic martensite).

The dependency of the damping capability on external loading conditions, like the range of strain amplitude, frequency and temperature has been studied by many research groups. Explicit observations from experimental investigations have been reported in relation to strain amplitude and temperature, whereas varying statements on the influence of frequency can be found in the literature. From the viewpoint of technical practice, there are applications subjected to a so called offset strain, arising in components under rotary motion. The main objective of this paper is to represent further experimental studies, which have been performed in order to obtain information about the influence of offset strains on the damping capability.

Uniaxial tension and compression tests on NiTi rods have been carried out with focus on varying frequencies and values for offset strains. The experimental evaluation reveals that the damping capability increases with the amount of offset strain, unless the reorientation strain is reached. Furthermore, the experiments show that an increase in frequency results in a decrease of damping capability.

Keywords:

1. INTRODUCTION

From a practical point of view, shape memory alloys are well known for their usage in applications for shape control or actuation and in mechanical components where large recoverable strains are required, like in eyeglass frames or medical stents. Such applications are either based on the thermal shape memory effect or the superelasticity. Besides these particular properties, the high damping capability is known as one of the important attributes, which at the same time is exploited with a lack of success [1]. The absorption of energy by means of mechanical loading is either related to the phase change from austenite into martensite and conversely or associated to the presence and mobility of phase and intervariant planar interfaces, depending on the state of the material [2].

Despite the high damping capability compared to other metallic materials, no real large industrial applications have been developed [1]. One of the reasons may be inadequate strain amplitudes during cycling resulting in insufficient damping values. Exploratory studies on tennis rackets and saw blades performed within the 1980's evidenced that the damping could be marginally improved but at the expense of other important qualities (weight, durability). A more successful application is the embedding of thin sheets in snow skies, showing a significant improvement in their performance [3]. Furthermore, a lot of research work has been carried out on devices for seismic protection, where large strain amplitudes in the order of 10^{-2} appear [4, 5]. For such high strains the pseudoplastic loading and unloading offers high damping capability because of the energy absorption which is proportional to stress-strain hysteresis [6].

Besides the passive usage of shape memory alloys for damping devices their active usage offers new possibilities for reducing noise and vibration. A new development was the incorporating of prestrained SMA wires into a polymer matrix in order to change the vibration frequency of such a 'smart material' component by means of a temperature increase. During heating the wires cannot return to their initial shape caused by the reverse transformation from the martensitic into the austenitic phase. The wires have to act against the stiffness of the polymer and this constraint leads to a generation of high recovery stresses and a shift in the resonance frequency. This concept is known in general terms as the active strain energy tuning (ASET), since a change of the model response is related to change in the energy balance [7]. Additionally to these methods two further procedures are known, named the active modal modification (AAM) and the active shape control. Within the first technique unstrained wires are embedded and a temperature increase leads to shift in the stiffness caused by the martensitic transformation. The second concept influences the shape of the polymer matrix which also influences the vibrational behaviour of the structure.

The overall scope of this research work is the vibration absorption of engineering structures by means of Nickel-Titanium based shape memory alloys. Besides obtaining an increase in damping induced by either superelastic or pseudoplastic loading, the intrinsic damping of thermo elastic martensite seems to be promising. In particular, thermo elastic martensite provides a higher damping capabilityat lower strain amplitudes compared to other metallic material systems [8]. The evaluation of the damping capability is essential for the development of applications for vibration suppression, in order to obtain maximum damping values depending on the loading conditions during operating time. There are some technical applications exposed to a so called offset strain during dynamic loading caused by centrifugal forces arising from rotational movement. Until today, numerous experimental investigations to determine the damping capability have been performed with focus on the dependency of the capability on strain amplitude, temperature and time [9-11]. In addition, further experiments have to be carried out in order to study the influence of offset strains on the damping capability. In view of the frequency, experiments at different strain rates have to be adopted in order to proof different observations that have been reported by various researchers.

This paper will begin with a briefly introduction of the damping capabilities obtainable during superelastic and pseudoplastic loading conditions. Recent experimental studies on thermo elastic martensite will be presented with focus on the dependency of the damping capability on offset strains and frequency.

2. DAMPING CAPABILITY OF SHAPE MEMORY ALLOYS

2-1. Energy loss during superelastic loading

Many research groups investigated the hysteretic behaviour of SMA wires in their superelastic condition to characterize the damping capability of those materials. The capability is related to the area of the hysteresis in the stress-strain path which is proportional to the energy absorbed. Loading cycles performed at different strain rates showed that an initial increase in strain rate leads to an increase in hysteresis, whereas beyond a certain strain rate the area decreases.

Piedboeuf found out that the maximum hysteresis can be reached at a strain amplitude of 4% at a cyclic frequency of 0.1Hz, which is a strain rate of $4{\cdot}10^{-3}s^{-1}$[12].

The observations on the dependency of the hysteresis area on strain rates have been proved by our own experiments on superelastic wires. The wires used for uniaxial tensile tests have a martensite to austenite transformation temperature around 0°C and are 0.152mm in diameter. Displacement driven tensile tests at strain rates of $7.87{\cdot}10^{-4}s^{-1}$, $1.57{\cdot}10^{-3}s^{-1}$ and $3.14{\cdot}10^{-3}s^{-1}$ were carried out in order to investigate the influence of the loading frequency. The tests were performed at room temperature, which ensures that the material was completely in its high temperature austenitic phase. The experimental results for the three different strain rates are plotted in figure 1.

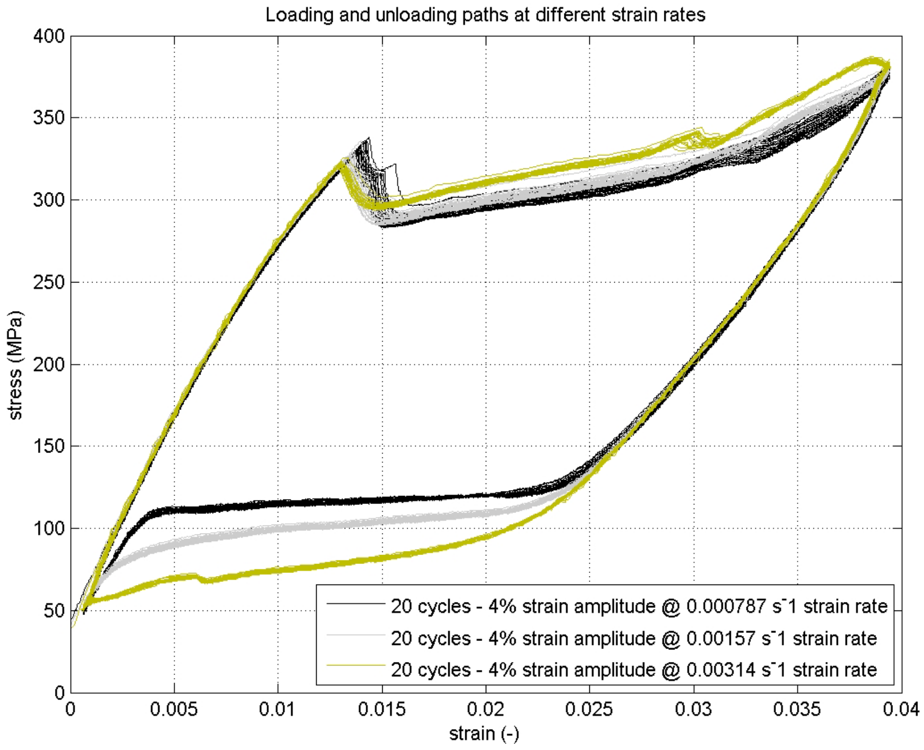

Figure 1. Hysteretic behaviour of SMA wires during superelastic loading at different strain rates

As reported by Lammering, the higher the strain rates the larger the hysteresis area, unless a certain strain rate is exceeded [13]. This observation could not be confirmed within the experiments performed in our laboratory because of the limitation in tested strain rates. From figure 1 it is clear that maximum damping values can only be achieved if the cyclic loading and unloading is fully within the hysteresis range. If one expects cyclic strain amplitudes of around 0.2%, which could be realistic for engineering applications, a so called basic or offset strain of 1.5% has to be applied. Consequently, the strain is oscillating between peak values of 1.7% and 1.3%.

Indeed, dissipative energy values up to 40% are conceivable in large structures such as buildings in seismic areas or in space structures subjected to vibrations [7]. For applications with small strain amplitudes one thinkable concept may be the structural prestraining of either the shape memory element or the complete structural component through an additional device in order to shift the loading path to the hysteresis and therefore achieving remarkable damping values.

2-2. Damping capability of thermoelastic martensite in SMA

The high damping performance of the martensitic phase is well known and related to the presence and mobility of the martensite variant interfaces and twin boundaries [7]. There are numerous studies and reports on alloy systems exhibiting such thermo elastic martensite transformations, e.g. Cu-Zn-Al, Cu-Al-Ni, Ni-Ti. Many investigations on the high damping capability of the thermo elastic martensite have been published and relevant references may be found in [1-4].

Extensive experimental investigations were performed in order to obtain information about the dependency of the damping capability on *frequency*, *strain amplitude* and *number of cycles*. The frequency parameter was conspicuously studied by Vandeurzen in Cu-Zn-Al, Ni-Ti and Cu-Mn alloys in the region between 10 and 150Hz [14]. Besides some variational peaks, no frequency dependency was detected. On the contrary, two authors recently observed and reported that with increasing frequency the damping capability (maximum strain energy divided by the dissipative energy) decreases. Because of those differing statements, further investigations should be carried out. With regard to the amplitude dependency, Koshimizu found out that one can distinguish between different amplitude domains [15]. There exists an amplitude-dependence range between strain amplitudes of 10^{-7} to 10^{-6}. Within the region of strain amplitudes of $5{\cdot}10^{-6}$ to 10^{-5} almost no amplitude dependency was observed.

The dependency on number of cycles has been investigated by Van Humbeeck et al. and Morin et al. for CuZnAl alloys and by Mercier et al. for Ni-Ti alloys [16]. The performed experiments lead to three statements: At constant amplitudes the damping decreases or goes through a maximum. The time dependence is controlled by temperature, strain amplitude and frequency. The decrease of damping at constant amplitudes can be restored by a change in the amplitude.

Finally, there is no unique damping value for one material. The damping capability is influenced by the external parameters - time, frequency, temperature and most important the amplitude. Additionally, the type of alloy, the martensite interface density and the grain size influence the damping capability. Compared to conventional engineering material systems, alloys with thermoelastic martensite provide a damping capability of at least an order of magnitude higher [van Humbeeck].

3. DAMPING CAPABILITY OF THERMOELASTIC MARTENSITE SUBJECTED TO OFFSET STRAINS

The main objective of the carried out uniaxial tension and compression experiments on Ni-Ti rods was the investigation of the influence of offset strains on the damping capability. In order to further examine the dependency of the damping capability on frequency, varying strain rates were adopted. In addition, the focus of testing was on strain amplitudes occurring in common industrial applications, in the order of 10^{-5} to 10^{-4}.

The Ni-Ti rods have a martensite to austenite transformation temperature starting at 65°C, identified by means of Differential Scanning Calorimetry. The objective of a single, displacement driven tension and compression experiment was the determination of the reorientation stress and corresponding strain value. Apparently, there is a residual tensile stress after loading (figure 2). The reason may be the fact that the specimen reaches a residual pseudoplastic strain, both after tension and compression loading. As it is a displacement driven cycle, the machine is forced to get back to its initial position and due to the compressive strain the rod is finally subjected to a tensile loading. The reorientation stress is about 290 MPa and the corresponding strain about 1.5%.

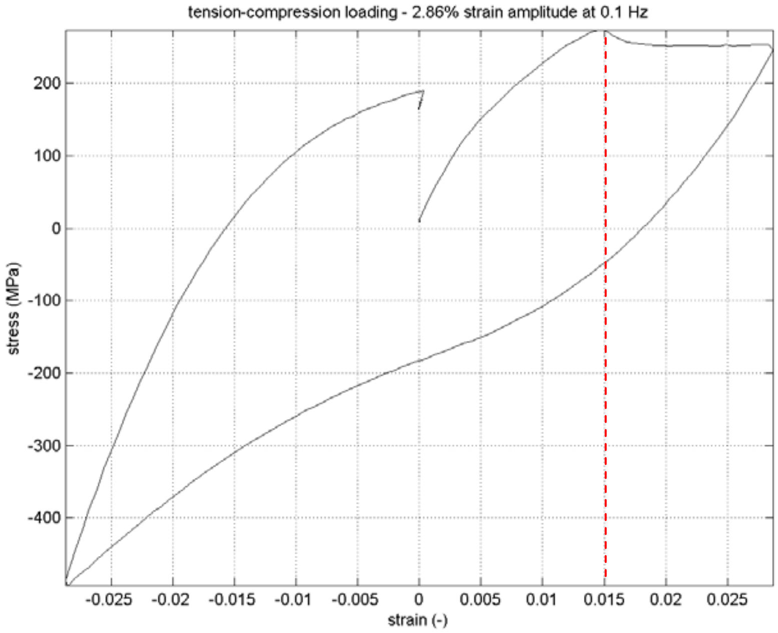

Figure 2. Tension and compression loading of thermo-elastic martensite

Indeed, the damping capability of SMA material during pseudoplastic loading is quite high compared to other metallic material systems, as long as the reached stress in every cycle is beyond the reorientation stress. Furthermore, the martensitic phase is well known for providing high damping capability at small strain amplitudes occurring in engineering applications. This type of damping is caused by the presence and mobility of all the different phase variants.

To distinguish the damping capability of specimens in the martensitic phase, sinusoidal displacement driven tests at amplitude values varying from 0.05% to 0.2% with a 0.05% interval were performed on a hydraulic driven testing machine. The major parameter, the offset strain, was varied between 0, 0.2%, 1%, and 2%. The strain range, which results from the combination of the respective offset strain and the applied strain amplitude, is either completely below or above the reorientation strain, which ensures that there is no pseudoplastic deformation during a single loading cycle and the damping capability is always related to the movement of the variants. In order to investigate the dependency on strain rates, frequencies of 1, 2, 5, 10 and 15 Hz have been adopted.

For each cyclic test, the loss of energy, namely Ψ, was calculated from the stress-strain diagrams and divided by the total strain energy, which is the sum of the tensile and compressive part. The results are plotted within the 3D histogram shown below in figure 3. As reported by [7], the higher the strain amplitude the higher the loss of energy. In contrast to [14] a frequency dependency could be proved. Generally, an increase in frequency corresponds to a decrease in the damping capability. Evidently, at 10Hz the energy loss seems to raise up, which has to be further examined. The second histogram (figure 4) compares the energy losses achieved at specific strain amplitudes and different frequencies and offset strain values. An increase in offset strain below the reorientation strain leads to a slight increase in the loss of energy, whereas an offset strain value beyond the reorientation strain results in a drop in the energy loss. The reason may be the fact that by achieving the reorientation stress, the martensite variants start to arrange along the preferred stress orientation and the amount of moveable phase interfaces reduces.

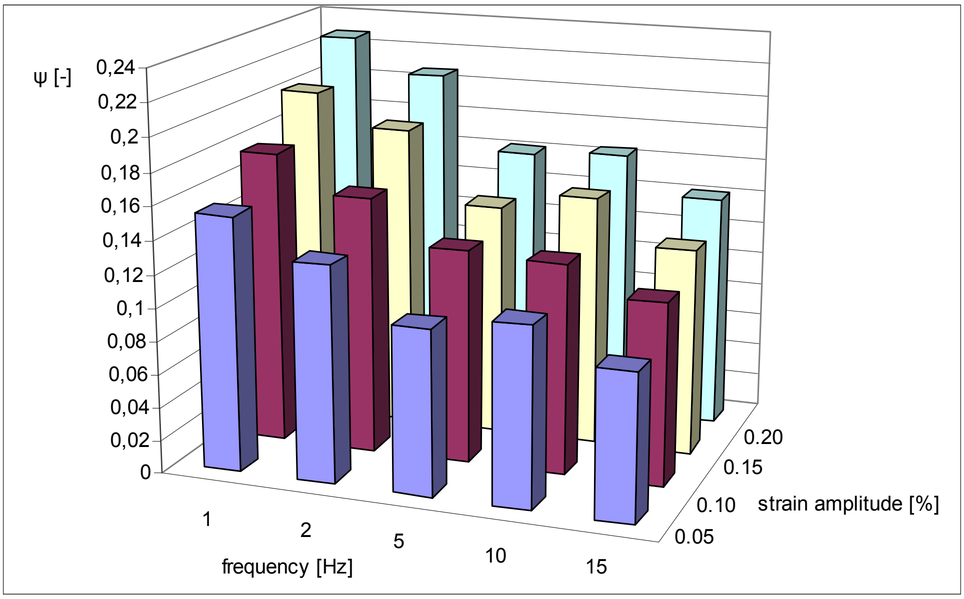

Figure 3. Loss of energy at 0.2% offset strain

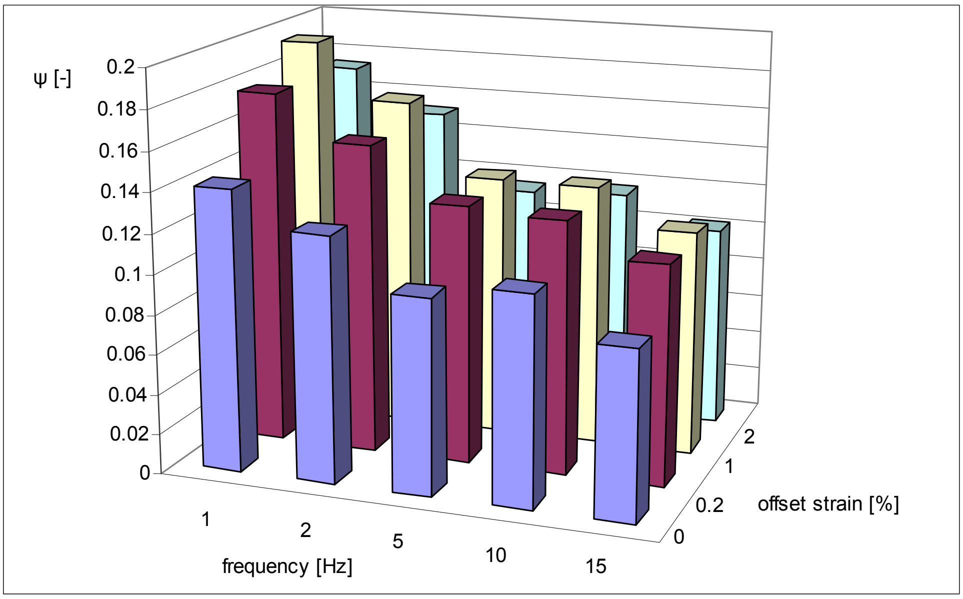

Figure 4. Loss of energy at 0.15% strain amplitude

4. CONCLUSION

A more general overview of developed applications for either passive or active damping by means of shape memory alloys has been given. The damping capacities achievable either by means of superelastic or pseuoplastic loading were compared. Numerous experimental investigations were performed by many research groups in order to determine the damping capability of shape memory alloys in their martensitic phase. Extensive studies on the influence of strain amplitude, time, temperature and frequency on the damping capability have been conducted.

There is a group of technical applications subjected to offset strains caused by rotational movement. The objective of the experiments performed within this framework was the investigation of the influence of such offset strains on the damping capability. The results revealed that there is a drop in obtainable damping capability if the offset strain is beyond the reorientation strain. In addition, the increase in damping capability below the reorientation strain seems to be related to the offset strain. To achieve maximum values for damping by means of thermoelastic martensite and small strain amplitudes, the offset strain has to be below the reorientation strain.

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