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THE APPLICABILITY OF SHAPE MEMORY ALLOYS IN STRUCTURES

O MOŻLIWOŚCIACH WYKORZYSTANIA STOPÓW Z PAMIĘCIĄ KSZTAŁTU W BUDOWNICTWIE

Abstract

The structural application of shape memory materials is relatively new. It is possible that these materials provide the unusual property of creating stress in steel bars in a thermomechanical way. Depending on the alloy composition and production treatment, the characteristic transformation temperatures as well as the mechanical properties of the material vary and this may limit its technical effectiveness. The present work is focused on the material parameters from the point of view of practice.

Keywords: *shape memory alloys; prestressing; concrete members*

Streszczenie

Zastosowania konstrukcyjne materiałów z pamięcią kształtu są stosunkowo nowe. Materiały te mogą prezentować nietypową właściwość wywoływania naprężeń w prętach stalowych wskutek reakcji termomechanicznej. Charakterystyczne temperatury przemian fazowych, a także właściwości mechaniczne stopu zależą od jego składu oraz procesu produkcji, co może mieć wpływ na techniczną efektywność materiału. Niniejsza praca dotyczy cech materiałów z pamięcią kształtu z punktu widzenia praktycznych zastosowań.

Słowa kluczowe: *materiały z pamięcią kształtu; sprężenie; elementy betonowe*

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1. Introduction

The cracking of construction materials is one of the major weaknesses which influence the durability of structures. The effect of local failure is irreversible regardless of the direct reason for damage, compression or tension, and also regardless the formulation – stress or strain. Concrete fails usually under tension, but high compression may also provoke cracks in the direction of the load. As well as other materials, masonry also shows cracks as a result of loads and deformations.

In order to limit the negative effect of cracks, various methods of reinforcing structural members are used. Steel reinforcing bars or steel profiles in concrete are passive – stress in this material appears only under an acting external load. Prestressing tendons are used successfully as active reinforcement in members of long spans or in members under high loads. In recent years, in addition to prestressing steel, new materials are also used for similar purposes – as fiber reinforced composite materials and shape memory alloys (SMA).

Particular properties of the SMA materials (memory effect and super elasticity) are used in medicine, aviation and mechanisms. Wide research has been carried out in the last 20 years in the scope of civil engineering applications. The advantages of such solutions are related to high corrosion resistance and the damping effect, but the main reason for research is investigating the effect of provoking tension in material in a thermo-mechanical as opposed to a mechanical manner. The number of successful applications, where the appropriately prepared tendons made of shape memory alloys are used, is increasing. Such tendons are installed in the structural member and after the activation of the thermomechanical effect they start to act with the internal forces. This proves the important possibilities related to the use of such material in building practice. Based on the existing information, it is possible to estimate the boundary parameters for such applications.

In order to describe the potential benefits from such applications, the most important characteristic parameters for the SMA materials are reported below. A selection of the results known from both the bibliography and local tests, including a quantitative description, completes the work.

2. SMA materials

Alloys which demonstrate the shape memory effect are composed of various metals. The name SMA is most commonly associated with nickel-titanium alloys – these are used widely in medicine i.e. as implants and in aeronautics. Other alloys are composed of cuprum, cadmium, zinc, aluminum, iron or manganese. Extensive descriptions of various compositions were published by Otsuka & Wayman ([1]).

2.1. Shape memory effect

The shape memory effect is commonly understood as strain recovery. In fact, SMA material may represent large initial deformation which is further recovered in effect of heating. The process is related to the transformation of the material between the austenite and martensite phases and governed by two key parameters: temperature and stress. The transformation process for a given alloy is formulated in the form of the transformation temperatures: A_s – temperature of the start of alloy transformation from the martensite to the austenite phase; A_f – temperature of the transformation finish from the martensite phase to the austenite phase; M_s – temperature of the start of alloy transformation from the austenite phase to the martensite phase; M_f – temperature of the transformation finish from the austenite phase to the martensite phase. Characteristic temperatures are usually measured for the given alloy at zero stress. Stress increase in the material results in the progressive increase of all transformation temperatures. The diagram shown in the Fig. 1 represents the fundamental formulation of the phase transformation.

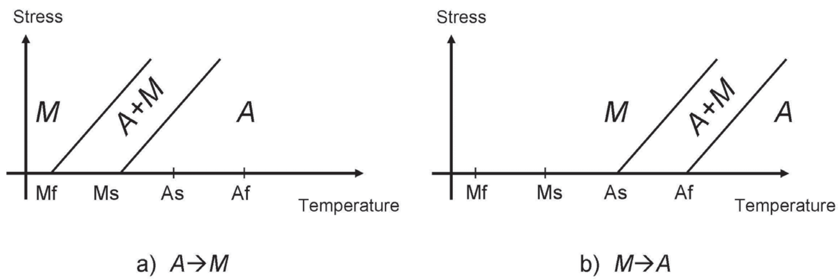

Fig. 1. Characteristic temperatures of the phase transformation for the shape memory alloys: a) – transformation from martensite to austenite, b) – transformation from austenite to martensite (description in text)

For any given alloy of two or more components, there are two principal parameters influencing the final properties of the material. The first of these is the proportion of different metals in the given alloy. Various results confirm that any variation of the proportions of a grade as small as 0.1% influences the transformation temperatures to a significant degree. The other is the alloy treatment after it melts. There are two technological solutions used: cold-working or hot-working processes. The influence of the working process on the mechanical parameters of the alloy is not negligible.

2.2. Mechanical and shape memory properties of SMA materials

Several mechanical properties are required to be estimated for the sake of the structural applications of the materials. As may be observed from the available data, NiTi alloy behaves in compression differently to tension (Otsuka & Wayman [1], Manach & Favier [2]).

Although the results were obtained for various materials, the general tendency is evident – the mean value of the modulus of elasticity in the martensite phase falls for tension values of around 34 GPa and for compression values of around 50 GPa. In the austenite phase, the mean values are 60GPa and 64GPa.

The yield limits for alloys under tension and compression present more important variations. In the martensite phase, under tension the mean yield limit is reported at 175 MPa, while the limit for compression is at 158 MPa. For the austenite phase, the yield value for tension is at 450 MPa, and for compression it is at 675 MPa.

The differences between the ultimate strength levels for both phases are much lower. For martensite under tension, the mean value is 1400 MPa and under compression, it is 1960 MPa. For austenite in tension – 1350 MPa and in compression – 1500 MPa. This means that the plastic behaviour of one of the two metallurgic forms of the material is largely different from the other – the ultimate stress at rupture is related more uniformly to the composition of the alloy. Table 1 provides the above mentioned values together with their tolerances.

Although the variation of the reported data is related partly to the alloy composition, it is necessary to underline that even for the material coming from the same production with identical chemical composition but formed in two different diameters, the mechanical properties are different. This is related to the technology used to form the wire. For structural applications, this means that the tensile strength is generally profitable – a low modulus of elasticity will limit the influence of the SMA reinforcement on the cross-section rigidity, but in any case, material testing in the final shape is required to measure its real properties.

From the range of parameters describing the memory effect demonstrated by the material, the recovered pseudo elastic strain and maximum recovery stress are important. These two parameters remain dependent from each other. For the stress recovery predeformation must be applied to the material and further results depend on it. Recovered pseudo elastic strain is generally higher than it is for conventional steel and reaches a level of 80‰ in tension as well as 60‰ in compression. The maximum recovery stress of even 800MPa for both directions of stress is the major argument confirming the potential effectiveness of SMA alloys in construction.

Table 1

Mechanical and shape memory properties of NiTi alloys

<table>
<tr><th>Direction of stress</th><th>Mechanical and shape memory properties</th><th>Martensite</th><th>Austenite</th></tr>
<tr><td rowspan="5">Tension</td><td>Modulus of elasticity [GPa]</td><td>34±18</td><td>60±35</td></tr>
<tr><td>Yield limit [MPa]</td><td>175±125</td><td>450±350</td></tr>
<tr><td>Ultimate strength [MPa]</td><td>1400±600</td><td>1350±550</td></tr>
<tr><td>Recovered pseudo-elastic strain [‰]</td><td colspan="2">80</td></tr>
<tr><td>Maximum recovery stress [MPa]</td><td colspan="2">800</td></tr>
<tr><td rowspan="5">Compression</td><td>Modulus of elasticity [GPa]</td><td>50±30</td><td>64±34</td></tr>
<tr><td>Yield limit [MPa]</td><td>158±33</td><td>675±125</td></tr>
<tr><td>Ultimate strength [MPa]</td><td>1960±160</td><td>1500</td></tr>
<tr><td>Recovered pseudo-elastic strain [‰]</td><td colspan="2">60</td></tr>
<tr><td>Maximum recovery stress [MPa]</td><td colspan="2">800</td></tr>
</table>

The values of the mechanical properties given above and in Table 1 represent an important scatter reflecting, amongst other parameters, the influence of the precise alloy composition. It therefore seems necessary to establish the characteristic parameters of the given alloy before further analysis of its participation in the structural work carried out. In further research, it should be considered whether the mechanical and shape memory properties are regularly related to the alloy composition. Nevertheless, the values confirmed with the tests show the potential opportunities related to the use of SMA materials in practice. Jank et al [3] presented the existing successful applications.

3. Application temperatures

From the point of view of practical applications, the precise estimation of transformation temperatures is of fundamental importance. The successful and durable introduction of internal forces in structural members may be ensured only if service conditions do not provoke changes of the material phase. As can be observed from the available data, transfer temperatures vary in relation to other conditions even for the same alloy proportions. In the following figure (Fig. 2), exemplary values of the transformation temperatures estimated in tests are presented. For the eleven tested NiTi alloys, the diagram shows the range of the following phases: martensite (A); transformation from martensite to austenite (B); between martensite start and austenite start (C); transformation from martensite to austenite (E); austenite (F). The violet range (D) for alloy 1 is characteristic for the alloy, where the temperature of the martensite start is higher than the temperature of the austenite start. Comparisons of the alloy parameters were reported by Hesse et al. [4] (alloys 1 and 2), Strnadel et al. [5] (alloys 3, 4 and 5), Manach & Favier [2] (alloy 6), Delgadillo-Holtfort et al. [6] (alloy 7), Destrebecq [7] (alloy 8) and Debska [8] (alloys 9, 10 and 11).

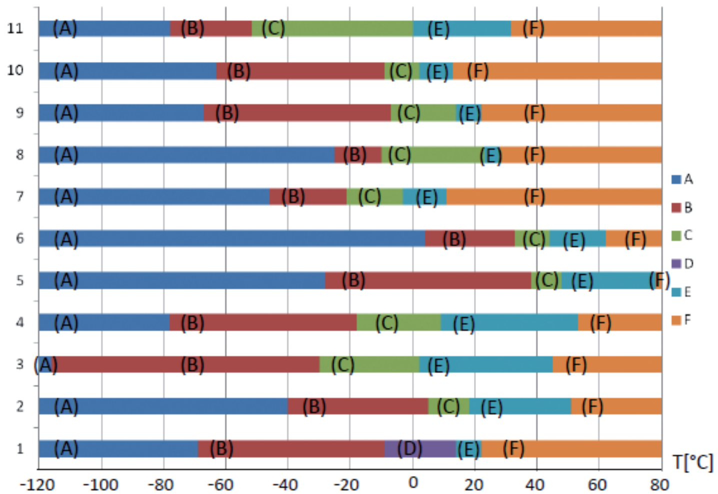

Fig. 2. Transformation temperatures for shape memory NiTi alloys (description in text)

An evident observation from the diagram is that depending on the alloy, the temperature of its potential use may vary substantially. On the other hand, for the given potential application, only a part of the available material will be suitable. For common temperatures during winter periods, which drop to –20°C, only some of the compared materials will not start the transformation from the austenite phase to the martensite phase, while the others will show a progressive decrease of the stress provoked by the shape memory effect.

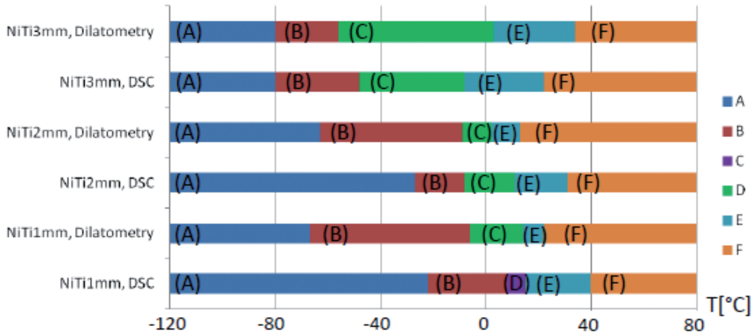

Fig. 3. Influence of the testing method on the estimation of the transformation temperatures (description in text)

An additional comment to the diagram in Fig. 2 refers to the reliability of the results of the transformation temperatures reported by the producers. Transition temperatures are estimated through the use of one of the two most popular procedures: differential scanning calorimetry DSC and dilatometry. The first of these methods is the more popular amongst producers, who supply the results of testing based on heat-flow scanning in the form of a diagram. Transformation temperatures are estimated using the intersection points of the tangent lines in the diagram. In the other method, material volume changes as the characteristic effects of phase transformation are observed. Both methods may give non-consistent results, as reported by Debska [8]. Fig. 3 shows a diagram built with use of the values based on the both methods. As may be observed in the diagram, transfer temperatures estimated using the dilatometry approach are higher. This is of importance for practical applications, where the transfer from austenite to martensitic in normal ambient conditions will eliminate the stress provoked by the shape memory effect. Shifting of the transformation temperatures for the alloy towards higher temperatures in effect of existing stress will additionally increase the risk of material transformation.

3. Stress-strain relationship

Beside the transformation process, the mechanical behaviour of the alloys is of interest due to their practical use. The stress-strain relationship built for the material will differ depending upon the phase at the beginning of the test. It is generally understood that the whole constitutive relationship will be shown properly if the test is starting from the austenite phase. An increase of stress from zero level will initially trigger a semi-elastic response from the alloy, followed by plastification and a yield-plateau. After phase transformation, the modulus of elasticity increases; finally the material reaches another plastification stress level and at increasing stress shows plastic deformation followed by rupture. The typical shape of the stress-strain diagram for the shape memory alloy is shown in Fig. 4.

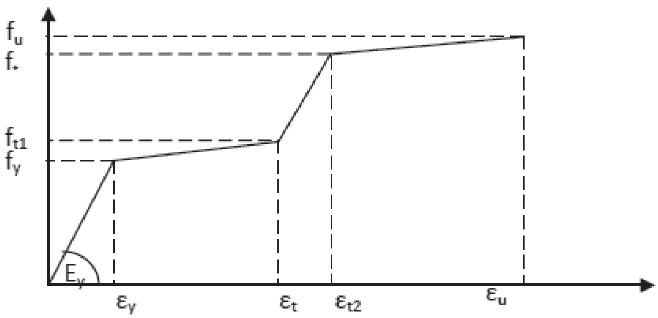

Fig. 4. Stress-strain relationship for SMA material

The Fig. 4 diagram follows the material behaviour under an increasing load starting from the austenitic phase. In the diagram, two sub-diagrams showing the behaviour for a metal are observed. Firstly, the material in the austenite phase shows a relatively high modulus of elasticity which drops after reaching the yield stress and strain, f_y and ε_y. After reaching a new limit of strain ε_t, phase transformation to martensitic material takes place and a stiffening effect represented by the higher inclination of the diagram line is observed. However, in this section sub-diagram the inclination of the line representing the modulus of elasticity is lower than in the first one. Finally, after reaching the second yield limit f_t, material stress increase slows down and ultimate stress f_u is reached.

From a practical point of view, this observation is important as the modulus for the martensitic phase is lower than the modulus for the austenite phase, while the modulus for the austenite phase is usually reported as the material characteristic value. In the conventional approach to the concrete members analysis, this means that the SMA reinforcement will be much less effective than passive reinforcement.

4. Conclusions

The mechanical characteristics of the shape memory materials depend on numerous parameters. From the point of view of practical use, it should be considered that:

– the mechanical parameters and transformation temperatures of the SMA alloys depend on the alloy composition and its treatment method during production;

– the application temperature should be in agreement with the transformation temperatures estimated for the given alloy with precision – for small diameters, the dilatometry method gives more reliable results;
– the temperature of the transformation should be corrected in order to account for the stress influence;
– structural applications should be analysed taking into account the whole stress-strain constitutive relationship and not only to a single value of the modulus of elasticity.

The promising properties of the SMA alloys require further research in order to establish more regular information on different aspects of its variation.

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