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Iron-based shape memory alloy strips, part 1: characterization and material behavior

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ABSTRACT: Shape memory alloys (SMAs) have a special characteristic, which is called shape memory effect (SME). SME means that the material returns to its initial shape after having been deformed. If the returning to the initial shape is prevented for instance by a mechanical fixation, stress develops in the SMA. In the form of ribbed bars and strips, the SMAs can therefore be used as prestressing elements in new reinforced concrete (RC) structures or for strengthening of existing RC structures. An iron-based SMA (Fe-SMA) was developed and patented at Empa. This Fe-SMA shows high tensile strength, excellent shape recovery stress (i.e. prestress force), high elastic stiffness, low material costs and simple manufacturing process in comparison to nickel-titanium (NiTi) based alloys. Recently, the developed Fe-SMA strip has been produced at an industrial scale. In this paper, experimentally determined properties of these Fe-SMA strips are presented. These Fe-SMA strips can be used as externally end-anchored reinforcement to strengthen the RC structures.

1 INTRODUCTION

New innovative methods to strengthen existing structures and to build new structures are necessary in the building industry. One set of such advanced materials are SMAs. SMAs have been around for a long time, but they have not been suitable for construction due to the expensive alloys (for example nickel-titanium, NiTi) from which they are made.

SMAs have a special property known as the “shape memory effect” (SME), in that, if they are deformed, they can return to the initial shape upon heating. The physical background for that behavior is the reversible transformation that occurs between the atomic crystal structures, austenite (face center cubic, fcc) and martensite (hexagonal-close-packed, hcp). Depending on the alloy, the SME either happens instantaneously after the force is released, an effect that is called “superelasticity”, or it can be activated by heating the alloy. The most commonly known SMAs are NiTi alloys. These materials are used in the automotive, aerospace, robotic, and biomedical domain (Mohd Jani et al. 2014). In addition to the SME, SMAs have other interesting properties and can therefore be used as self-centering elements, dampers, sensors, or actuators. There is a considerable amount of literature on the topic of SMAs and their application in the construction industry (Cladera et al. 2014).

At Empa, extensive studies on SMAs for civil engineering applications have been done over, approximately, the last 15 years (Czaderski et al. 2015). In the early 2000’s, possible application ideas were mainly for NiTi-SMAs, such as controlled or fixed prestressing, superelasticity with low energy dissipation and for sensors (Czaderski and Motavalli 2003). In 2003, a concrete beam was longitudinally reinforced with SMA wires at Empa (Czaderski et al. 2006). In 2003/2004, NiTi-SMA wires were embedded in mortar to demonstrate the feasibility of prestressed short fiber reinforced concrete (Moser et al. 2005). The total fiber content was 1.2% in volume. A compression stress of approximately 5.7 MPa in the concrete prisms was determined.

The objective of a PhD thesis work in 2004 was to find possible applications for SMAs in structural engineering. An overview was published in 2005 (Janke et al. 2005). From 2005 to 2008, a new Fe-SMA for civil engineering applications was developed at Empa (Dong et al. 2009). The composition of the developed alloy was Fe–17Mn–5Si–10Cr–4Ni–1(V, C) (mass%). For civil engineering applications, Fe-SMAs represent a promising technology for a number of applications because of their properties and lower cost when compared to NiTi. The newly developed Fe-SMA can be activated at temperatures between 100°C and 160°C by resistive heating over a short period of about one minute. Furthermore, it can be produced on an industrial scale under atmospheric conditions without the need for expensive, high vacuum processing facilities. For different applications, it can be manufactured in appropriate shapes such as bars, strips, wires, foils, etc. by hot and/or cold forming. Empa patented the Fe-based SMA in 2008.

In 2012, in parallel to investigations on the behavior of the developed Fe-SMA, a feasibility study began on the usage of Fe-SMA for the strengthening of reinforced concrete structures (Czaderski et al. 2014, Shahverdi et al. 2015, Shahverdi et al. 2016). The idea was to use Fe-SMA strips as near surface mounted (NSM) reinforcement. In this project, several RC beams were strengthened with the NSM technique using Fe-SMA strips (Shahverdi et al. 2015, Shahverdi et al. 2016). The stress-strain behavior and the recovery stresses of the Fe-SMA strips were measured. The recovery stress (i.e. the prestress force) after prestraining to 2 or 4% and heating to 160°C was in the range of 250 - 300 MPa (Czaderski et al. 2014). In addition to Fe-SMA strips, in another project, ribbed Fe-SMA bars were produced for strengthening of RC structures in combination with shotcrete (Shahverdi et al. 2016).

In this paper experimentally determined material properties of the recently produced Fe-SMA strips at an industrial scale are presented. Recovery stress and recovery strain have been measured. Effects of prestraining and maximum heating temperature on the obtained recovery stress (i.e. prestress) have been studied. In a companion paper (Michels et al. 2017) the application of Fe-SMA strips as an external end-anchored and unbonded prestressing system for structural retrofitting is presented.

2 PRODUCTION OF THE FE-SMA STRIPS

Recently, a novel iron-based shape memory alloy was developed at Empa (Dong et al. 2009). In past, only laboratory-scale production of around 100 kg was possible. However, recently the company re-fer AG in collaboration with a stainless steel producer has manufactured Fe-SMA strips at a larger industrial scale. Roughly, the following steps were performed: First, a batch of approximately 8 tons of the alloy with the same composition as described in (Dong et al. 2009) was produced. Subsequently, billets with a size of approximately 130×130×4000 mm^3 were produced. In the next step, a billet was heated in an oven to a temperature higher than 1100°C, and the cross-section of the block was reduced to approximately 3 mm×150 mm by hot-rolling. After this process, strips with a final thickness of 1.5 mm and 0.5 mm by width of 100 mm and

50 mm, respectively, were produced by a few cycles of cold-rolling. As seen in Figure 1, large batches were produced.

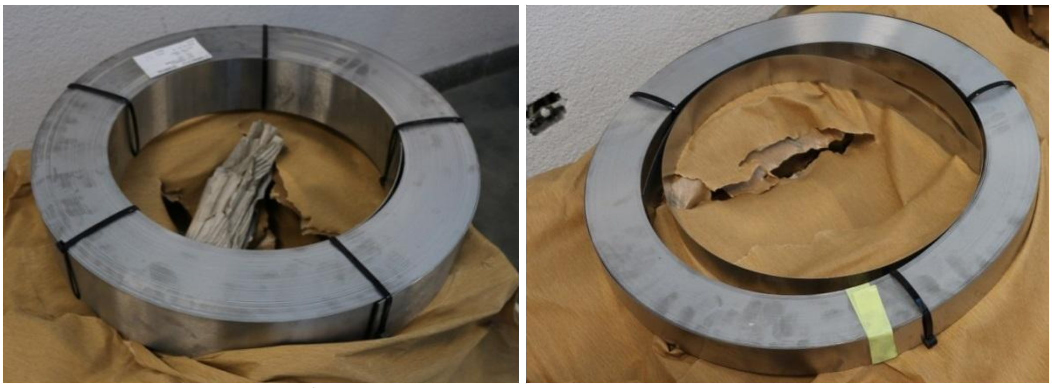

Figure 1. Fe-SMA strips. Left: 1.5 mm thickness and 100 mm width, Right: 0.5 mm thickness and 50 mm width

3 EXPERIMENTAL PROGRAM

3.1 Specimen geometry and cutting

Test specimens of length 260 mm and width of 15 mm were cut out from the received Fe-SMA strips for the material characterization, see Figure 2. In case of the 1.5 mm thick strips, two different cut out have been taken, one in the middle and one on the border. For the 0.5 mm thick specimens, only central samples were tested.

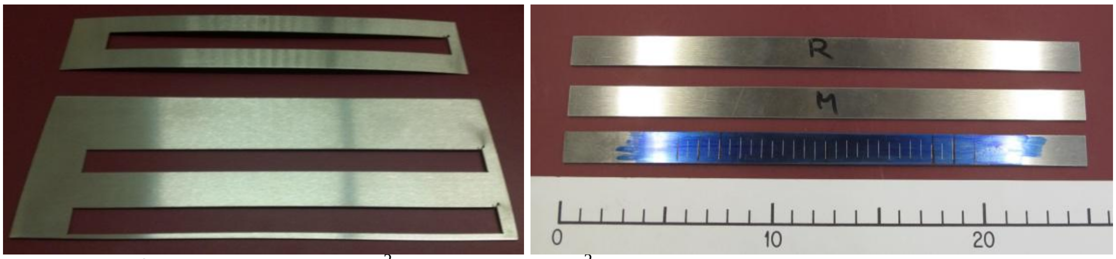

Figure 2. Left: original 50×0.5 mm^2 and 100×1.5 mm^2 strips with cut out samples. Right: Fe-SMA strips before the tensile test, marks for the strain measurements. (dimensions in mm).

3.2 Tensile test set-up

Tensile experiments at room temperature (RT) were performed up to failure in a 200 kN tensile testing machine of type Zwick 1484. An extensometer of the Zwick Makro type was used for the strain measurement, Figure 3.

3.3 Prestraining and activation experimental set-up

Before the activation of Fe-SMA strips, the samples were prestrained at RT by a 20 kN Zwick machine. The experiments were performed under (machine) displacement control at a rate of 1 mm/min. The strain was measured with an extensometer with a gauge length of 100 mm. After the planned prestrain was reached, the load was completely released (machine displacement controlled at a rate of 0.5 mm/min).

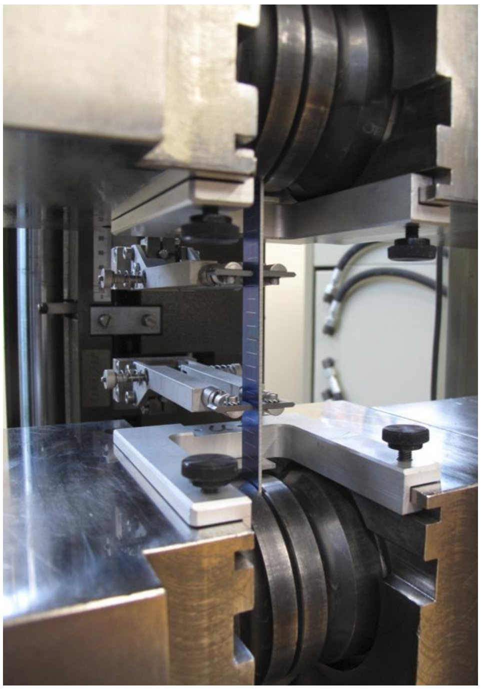

Figure 3. Fe-SMA strips installed in a Zwick testing machine equipped by an extensometer over a length of 100 mm [Empa report Nr. 5‘214‘009‘925].

Figure 4. A 20 kN Zwick machine equipped with a climate chamber. The machine was used for prestraining and activation of the Fe-SMA samples.

For the heating experiments, a climate chamber was added to the tensile testing machine. Figure 4 shows the climate chamber, the clamps, the Fe-SMA test specimen and the extensometer. A special clip-on extensometer with a gauge length of 100 mm was used for the heating experiments. The temperature expansion of the extensometer was continuously compensated during the experiments by a control in the testing machine.

At the start of the heating experiments, the Fe-SMA test specimens were loaded to a preload of approximately 50MPa to avoid compression in the test specimens during heating due to thermal expansion. Then, while the testing machine held the strain constant (i.e., a strain change of zero), the temperature was increased from 23°C up to a “target temperature” at a rate of 2°C·min-1. After a waiting time of one (or two) hours at the “target temperature”, the temperature was decreased again at a rate of approximately 2°C·min-1 down to 23°C. The tensile stresses in the Fe-SMA strips after a further waiting time of one (or two) hours at 23°C were taken as the “recovery stress”.

The effects of the following parameters on the obtained recovery stress were studied.

- Effect of prestraining
- Effect of cutting position
- Effect of maximum heating temperature

In another series of experiments, the behavior of the activated Fe-SMA strips subjected to axial tensile loadings was studied. In such experiments, after the activation process, the strips were remained in the machine and an additional loading was applied. The strains were then recorded by means of an extensometer.

4 RESULTS AND DISCUSSIONS

4.1 Stress-strain behavior up to failure

The stress-strain behaviors of the examined strips under axial tensile loading are depicted in Figure 5. The Fe-SMA strips had an ultimate tensile strength $f_{SMA,u}$ of about 1000 MPa with a corresponding strain at failure $\varepsilon_{SMA,u}$ of minimum 47% and 42% with a thickness of 0.5 mm and 1.5 mm respectively. Both type of strips showed a very ductile behavior compare to common reinforcing materials in concrete construction. No difference between the border and middle samples could be observed for the 1.5 mm thick strips.

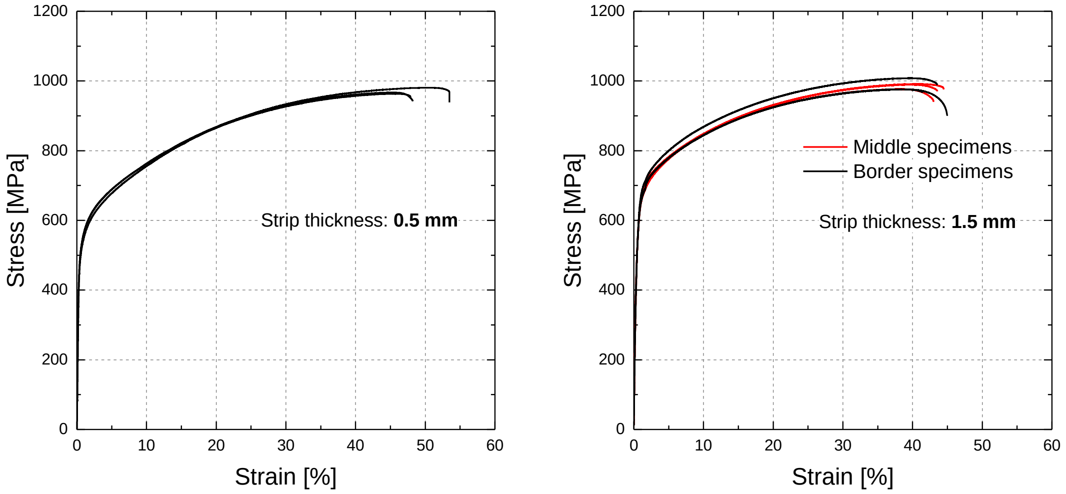

Figure 5. Stress–strain diagrams of tensile experiments of the Fe-SMA strips. Left: strip with thickness of 0.5 mm. Right: strip with thickness of 1.5 mm from the middle and border.

4.2 Recovery stress

In this section, recovery stresses obtained from the constrained heating and cooling tests are presented. Effects of different parameters on the final recovery stress are then discussed.

4.2.1 Effect of prestraining on recovery stress

The obtained recovery stress depends on the amount of prestraining before the activation. Figure 6 shows the effect of strip prestraining on recovery stress versus temperature curves for the 1.5 mm thick Fe-SMA strips subjected to maximum temperature of 160 C. According to the obtained results, prestraining of 2% maximizes the recovery stress. Prestraining more than 2% did not lead to any increase in recovery stress.

4.2.2 Effect of maximum heating temperature on recovery stress

Figure 7 shows the comparisons between the recovery stress versus temperature curves for the specimens subjected to three different maximum heating temperatures of 120, 160, and 195°C. The strips of 1.5 mm in this study were prestrained to 2% prestraining before the activation. The recovery stress obtained by cooling the specimens down to room temperature were higher for the strips subjected to a higher maximum temperature, see Figure 7.

The trend of the effect of maximum temperature on the obtained recovery stress is depicted in Figure 7 right. It is expected that the increasing trend reaches a plateau. Due to the limitation of the experimental setup, temperatures above 200°C were not possible. However, further investigations in the structural engineering research laboratory at Empa are ongoing to determine the plateau.

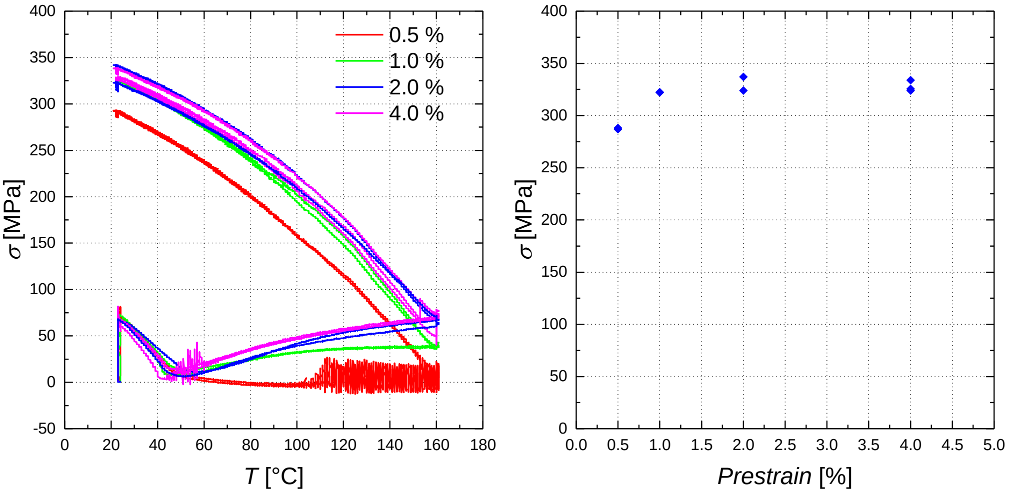

Figure 6. Effect of strip prestraining on recovery stress versus temperature curves for the 1.5 mm thick Fe-SMA strips subjected to a maximum temperature of 160°C.

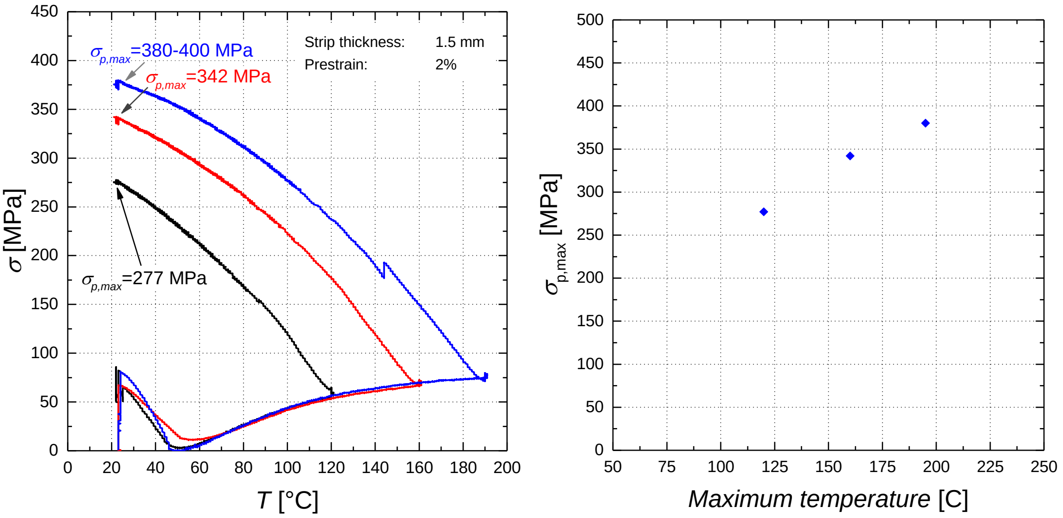

Figure 7. Effect of maximum temperatures on recovery stress versus temperature curves for the 1.5 mm thick Fe-SMA strips subjected to 2% pre-strain.

4.2.3 Effect of cutting position on the recovery stress

Figure 8 shows the comparisons between the recovery stress versus temperature curves for the specimens cut out from middle and border from strip with thickness of 1.5 mm (Figure 2). Strips were subjected to 4% prestraining before the activation and heated to a maximum temperature of 160 C. The recovery stress obtained by cooling the specimens down to room temperature were approximately the same for both cuts, see Figure 8. However, the SME seems to start at a higher temperature for the middle strips.

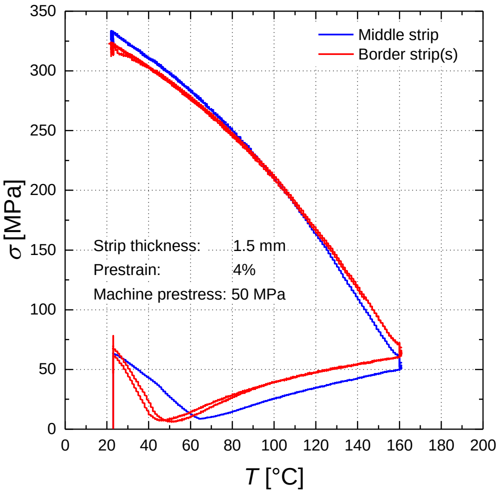

Figure 8. Effect of strip position cut on recovery stress versus temperature curves for the 1.5 mm thick Fe-SMA strips subjected to 4% pre-strain.

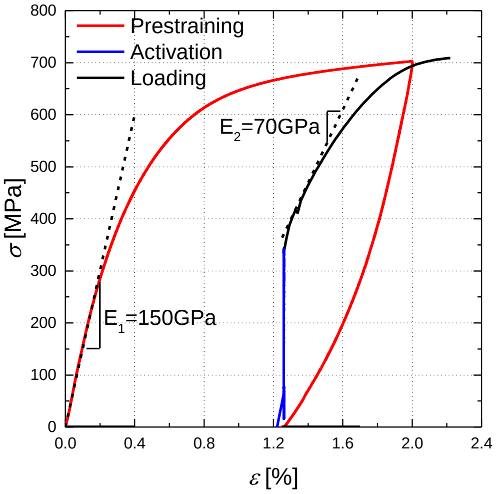

Figure 9. Stress-strain behavior of a 1.5 mm thick Fe-SMA strip prestraining to 2%, activation by maximum temperature of 160°C, and subjecting to a tensile load after activation.

4.3 Loading after activation

An important aspect for the application of the prestressed Fe-SMA strips is their behavior under additional load after activation. Such a load can be considered as the service load in constructions. Knowledge about this behavior is needed for the design of real applications. Figure 9 shows the stress-strain behavior of a representative experiment. The stress-strain curve of the additional loading is reaching the initial curve; however, the Young's modulus is different. For the design purpose, such Young's modulus shall be used.

5 CONCLUSIONS

Material characterization of the recently in an industrial level produced Fe-SMA strips were performed in this study. The characterizations are on the engineering level for the purpose of application in civil engineering structures. Further investigations in the atomic scale, however, could support the findings. The following conclusions were drawn:

- The Fe-SMA strips produced in an industrial level by the company re-fer AG showed excellent properties. They showed a very ductile behavior prior to failure. The ultimate tensile strength $f_{SMA,u}$ of about 1000 MPa with a corresponding strain at failure $\varepsilon_{SMA,u}$ of more than 40% was obtained. Recovery stress of 300-350 MPa were measured after heating the Fe-SMA strips to 160°C
- The cutting position did not have any significant effect on the obtained recovery stress. Thus the material behaves uniformly along the whole width of 100 mm.
- The amount of prestraining influenced the obtained recovery stress. For the studied Fe-SMA strips, prestraining of 2% maximizes the recovery stress.
- Activation by higher temperatures leads to a higher recovery stress. It is expected that the increasing trend reaches a plateau. Investigations are ongoing to determine such plateau.
- Loading the Fe-SMA strips after activation showed that their stress-strain curve will overlap the stress-strain curve for the tensile experiments. However, the Young's

modulus is different just after the activation (approximately half of the one for the initial prestraining). This Young's modulus shall be used for the design purposes.

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