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Review

Iron-based shape memory alloys for civil engineering structures: An overview

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HIGHLIGHTS

- The development of iron-based SMAs is presented, focusing on features for civil engineering.
- Differences between the martensitic transformation in Ni–Ti and Fe–Mn–Si SMAs are highlighted.
- High recovery stresses, which are necessary for prestressing, can be obtained for FeMnSi alloys.
- Pilot experiences on the application of FeMnSi alloys are presented.
- This paper collects unsolved aspects for future research.

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ABSTRACT

Iron-based shape memory alloys (SMAs), especially Fe–Mn–Si alloys, are materials that have great potential in civil engineering structures, but their application is still in a pioneer stage. Recent developments in alloy composition and manufacturing envisage new perspectives, especially in the field of repairing structures as well for new structures, when using these SMAs as prestressing tendons. This paper presents the fundamentals of the martensitic transformation from an engineering perspective as well as some key properties, such as recovery stress, corrosion resistance, weldability and workability. Finally, some unsolved aspects are collected, and new perspectives for the use of these SMAs are presented.

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1. Introduction

Shape memory alloys (SMAs) are unique materials that have the ability to achieve great deformations and to return to a predefined shape after unloading or upon heating [1]. This shape memory effect is the result of the reversible phase transformation that SMAs undergo, the so-called martensitic transformation. The martensitic transformation can be produced by changes in temperature or by the action of stresses. In the former case, the martensitic transformation takes place at defined temperatures (Fig. 1). The martensitic transformation, or forward transformation, is induced upon cooling the austenite phase (stable at high temperatures), and consists of the appearance of the martensite phase (stable at low temperatures). In the absence of applied stresses, the temperature at which the process begins is known as M_s (martensite start), whereas M_f (martensite finish) is the temperature at which the transformation finishes (Fig. 1). If the material is in martensite ($T < M_f$), then the reverse transformation can be induced by heating the material. The formation of austenite will start at temperature A_s (austenite start) and will finish at temperature A_f (austenite finish). The transformation shows thermal hysteresis, in other words, the forward and reverse transformations do not take place at the same temperature [2].

The first discovery of a material with shape memory was documented by Chang and Read, who observed a reversible phase transformation in an Au–Cd alloy [1]. Buehler et al. discovered in 1962 the shape memory effect in a Ni–Ti alloy [3], a fact that led to the boom in international research in this field and the appearance of the first real applications of these alloys. Since then, different types of alloys with the shape memory effect have been discovered. Ni–Ti alloys, in some cases having a third component, are the ones that, to date, hold the first position in the industrial market. The main drawback of these alloys for their application in civil engineering structures is their cost. In 1982, the shape memory effect (SME) in an Fe–Mn–Si alloy was discovered [4], and since then, new iron-based SMAs with improved SME properties have been developed. It is assumed that this progress will contribute to lowering the price of these materials and to making them much more competitive for civil engineering applications.

Janke et al. [5] presented possible applications of SMAs in civil engineering structures: passive vibration damping and energy dissipation, active vibration control, actuator applications and the utilization of the SME for tensioning applications or sensors. However, these authors stated that due to the size of the civil engineering structures and the actions of relatively high forces, low cost SMAs were needed.

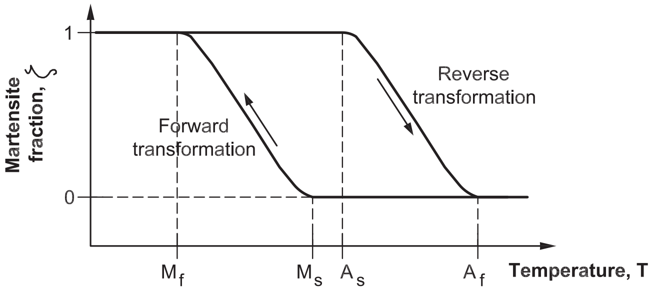

Fig. 1. Schematic definition of the forward and reverse martensitic transformation temperatures.

The repairing of structures using the SME for prestressing tendons is a promising field for the use of iron-based SMAs, as well as their use in new structures. If iron-based SMAs can be used for prestressing applications, they have several advantages compared to the traditional prestressing/posttensioning technologies, for example, there are no friction losses, no anchor heads or ducts are required, and no space is necessary for applying the force with a hydraulic device. The reason is that the prestressing of the SMA tendons is not performed mechanically, as in conventional prestressing steel, but with heating, as will be explained later in this paper.

There are two different groups of iron-based SMAs [6]. The first group contains alloys such as Fe–Pt, Fe–Pd and Fe–Ni–Co, which exhibit the typical characteristics of thermoelastic martensitic transformations similar to Ni–Ti, with a narrow thermal hysteresis. However, in spite of extensive studies, no pseudoelasticity at room temperature has been reported with Fe–Pt or Fe–Pd alloys. In 2010, Tanaka et al. [7] presented an Fe–29Ni–18Co–5Al–8Ta–0.01B (mass %) SMA that shows a recovery strain of over 13% at room temperature and a very high tensile strength of 1200 MPa, placing it at the cutting edge of knowledge as far as new materials are concerned [8,9]. This iron-based SMA could be very useful for applications that are related to pseudoelasticity and damping capacity. Additionally, good superelastic properties at room temperature have been found in an Fe–36Mn–8Al–8.6Ni (mass %) alloy [10], with a recovery strain of over 5% and a fracture tensile strain of over 8%. However, these two new alloys still need further development to be able to produce them in large amounts for real-scale elements in the construction industry, and the cost of the material would most likely be too high for construction standards because they should be cast in special conditions due to their composition.

The second group is a group of alloys such as Fe–Ni–C and Fe–Mn–Si, which have a larger thermal hysteresis in transformation but still exhibit the SME. The Fe–Mn–Si SMAs have received considerable attention over the past two decades due to their low cost, good workability, good machinability and good weldability [11], although the real applications are still limited except for some remarkable exceptions, i.e., large size joining pipes for tunnel construction and crane rail joint bars [6].

The SME of the Fe–Mn–Si alloys is attributed to the stress-induced martensite transformation from a parent γ-austenite (fcc – face-centered cubic) phase to an ε-martensite phase (hcp – hexagonal closed-packed) (Fig. 2) at low and intermediate temperature and the reverse transformation (ε- to γ-phase) at high temperature. In fact, it had long been known that Fe–Mn alloys could undergo this transformation, but the desired SME had not been obtained [12]. The problem was that for high amounts of Mn, γ-austenite was stabilized, making it difficult for the stress-induced martensitic transformation to occur. On the other hand, for lower amounts of Mn, when the alloy was subjected to stress, not only ε-martensite but also α'-martensite (bct – body-centered tetragonal) was generated (Fig. 2c). This phase is irreversible. The occurrence of α'-martensite induces dislocations markedly, preventing the SME from developing [12]. Sato and his co-workers discovered that the addition of Si allowed having the SME [4]. It was also observed that Cr, among other elements, was effective to a minor extent. This finding suggested that Cr was suitable as a