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Review

Reconciling viability and cost-effective shape memory alloy options – A review of copper and iron based shape memory metallic systems

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ABSTRACT

Shape memory alloys (SMAs) are group of alloys that display anthropomorphic characteristics. These alloys recover their pre-deformed morphology when heated above their transition temperatures after being deformed in their lower temperature phase (martensitic phase). This unique material behavior is explored in industrial and technological applications where capacity for strain recovery is a key design parameter. Copper and iron based SMAs are largely viewed as potential cost effective substitute to Ni–Ti SMAs judging from their promising shape memory properties, damping capacity and other functional properties. Despite their outstanding potentials, the susceptibility of copper based SMAS to phase stabilization, transition hysteresis, aging and brittleness creates doubt on the possibility of transiting from the realm of potential to functional long term use in engineering applications. On the other hand the low percentage shape recovery in the Fe based SMAs also creates a gap between the theory and potential use of these alloys. This paper takes a critical look at the science of shape memory phenomena as applicable to copper and iron based SMA systems. It also covers the limitations of these systems, the effect of processing parameters on these alloys, proposed solutions to limitations associated with this group of shape memory alloys and thoughts for future consideration.

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1. Introduction

The quest to ably address the rising sophistication, complexity and stringency in service requirements for materials has propelled the advancement in material design and development. Several 'super-functional' materials referred to as advance materials which combine unique engineering properties are now being processed for commercial use. A class of advance material which is attracting lot of attention presently is shape memory alloys. Shape memory alloys (SMAs) are primarily characterized by the capacity to restore their original dimensional integrity (pre-deformed shape and size) after undergoing substantial deformation when heated to a certain temperature [1]. This temperature induced strain recovery and other elasticity variants exhibited by SMAs over most other engineering materials (Fig. 1) have made them more appropriate for use in a number of applications. These includes biomedical (blood clot filters, orthodontic corrections), industrial (fluid connectors and coupling), thermal actuators (fire alarms, fire safety valve) and other domestic applications (eye glass frames, brassieres underwires) [2].

Shape memory transformation was first observed when gold-cadmium samples displayed extensive elasticity in a study carried out by Olander in1932. The phenomena has since been observed in a number of metallic systems like Ag–Cd, Au–Cd, Cu–Al–Ni, Cu–Sn, Cu–Zn, Cu–Zn–X (X = Si, Sn, Ga, Al), In–Ti, Ni–Al, Ni–Ti, Mn–Cu, Fe–Pt, Fe–Mn–Si [3]. The NiTi system remains the most functional, successful and commercially utilized SMAs but its complexity and cost has limited its use in commercial applications. The Cu based alloy systems and Fe based systems are next in ranking of shape memory properties and have significant cost advantages over the NiTi system.

Iron based SMAs have been reported to undergo certain amount of shape recovery. These alloys have good workability and can be produced via conventional steel making processes, and have a cost advantage over NiTi alloys [4]. The Cu based systems are reported to exhibit superior shape memory functionality compared to the Fe systems and also has a relatively low processing cost advantage [5]. This has made Cu based alloy systems the long term proposed alternatives to the NiTi alloy ahead of the Fe systems for shape memory applications. Despite the cost advantages alongside modest shape memory properties, these alloys (Cu and Fe based SMAs) are yet to replace NiTi alloys in several applications where they have to compete for selection. This has somewhat slowed down the practical exploitation and commercial endorsement of shape memory alloys in a number of application. Several articles have been written to review the shape memory phenomena of NiTi, Cu based and Fe based alloys [3,6–10]. There are however sparse literatures which have attempted to fuse in one review, the fundamental theories of the shape memory phenomena as well as take a critical look at some of the viable low cost SMAs (Cu and Fe based alloys).

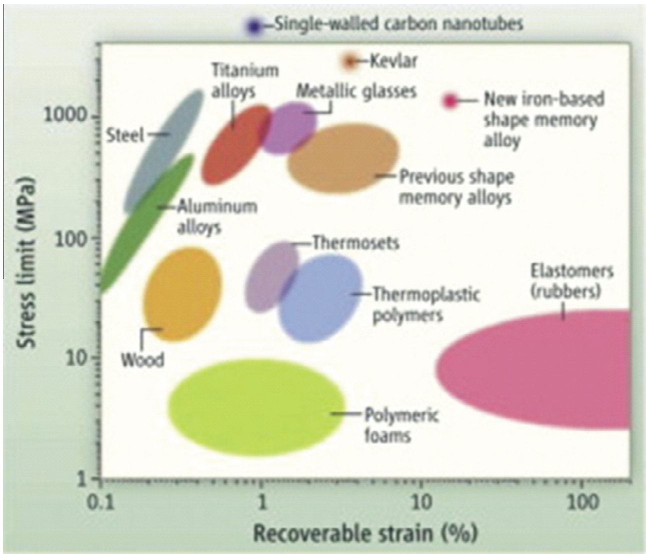

Fig. 1. Typical stress limits and recoverable strain of SMAs compared with other engineering materials (after Jani et al. [9], with permission from Elsevier).

2. Theories of shape memory phenomena

Shape memory materials exhibit certain properties that characterize their uniqueness and behavior. These materials have two basic phase systems a higher temperature austenitic phase and lower temperature martensitic phase [11]. The transition between the phase systems in these materials is what is known as the shape memory transformation. The driving force for this transformation is the difference in the Gibbs free energy of the phases and can be temperature or stress induced [12]. The temperature or stress dependencies are properties which influence the shape memory behavior of materials.

2.1. Thermoelasticity (thermoelastic transformation)

2.1.1. Martensitic transformation

The martensitic transformation is one of the most pervasive phase transformations observed to occur in a number of material systems including metallic, polymeric and ceramic systems [13]. This transformation is a diffusionless solid to solid shear transformation from a higher temperature phase which results in the formation of martensite. The material transforms from a greater crystallographic symmetry phase (austenite phase) to a lower symmetry martensite having multiple symmetry related variants [8]. Martensitic transformations can be thermoelastic (nucleation independent) or non-thermoelastic (nucleation dependent transformations in ferrous alloys).

2.1.2. Shape memory effect

Shape memory effect (SME) is a manifestation of thermoelastic martensitic transformation which is a nucleation independent transformation. It describes the phenomenon where materials assume a particular shape upon deformation in the martensite phase but reverse their original shape (dimension) prior deformation when subjected to temperatures above their transition temperature [14].

The austenite phase which is the high temperature phase is the stronger of the two phases with an opened structure which is either body centered cubic (bcc) or face centered cubic (fcc). The martensite phase is the lower temperature soft phase with a closed structure which is either hexagonal closed pack (hcp) or orthorhombic or monoclinic and easily deformable [12]. Marten-

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