Shape Memory Effect in Nitinol

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Abstract: A notable set of 'smart materials', Shape Memory Alloys (SMAs) provide the potential for a variety of applications. They have the ability to regain their original shape even after apparent plastic deformation or 'memorise' when subjected to certain stimuli such as thermomechanical or magnetic variations. The same materials, in a certain temperature range, can be strained up to approximately 8.5% and still will return to their original shape when unloaded. These unusual effects are called thermal shape memory and superelasticity (elastic shape memory) respectively. These phenomena occur due to a reversible phase change known as thermoelastic martensitic transformation. The shape memory effect can be used to generate motion and/or force while superelasticity can store deformation energy.

Since the discovery of superelasticity exhibited by an Au-Cd alloy by Arne Ölander in 1932, SMAs have been implemented in a broad range of applications due to their unique properties. These include consumer products and industrial applications: structures and composites, automotive, aerospace, mini actuators and micro-electromechanical systems (MEMS), robotics, biomedical and even in fashion. Iron-based and copper-based SMAs, such as Fe– Mn–Si, Cu–Zn–Al and Cu–Al–Ni, are low-cost and commercially available, but are not ideal for most applications due to their instability, brittleness and poor thermomechanical properties. Therefore, Ni-Ti alloys are preferred in most cases. [1] This report covers the thermomechanical shape memory behaviour of nitinol, a Ni-Ti shape memory alloy. (Named after its composition and place of discovery: Naval Ordinance Laboratory)

1. THE Ni-Ti SYSTEM

Ni-Ti alloys generally have a composition of around 50 at.-% or 55 wt.-%. The shape memory phenomena generally involve two phases: the austenitic parent phase at higher temperatures and the metastable martensitic phase at lower temperatures. The austenitic phase has a CsCl-type B2 superlattice ($Pm\overline{3}m$) while the martensitic phase displays a close-packed B19' monoclinic structure ($P2_1/m$) as shown in Fig. 1 [2]. There also exist some other phase transformations involved with shape memory such as rhombohedral, bainite and rubber-like martensite, which will not be discussed in detail.

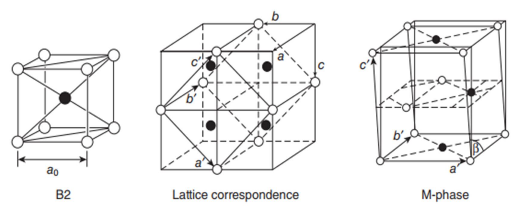

Fig. 1: Lattice structure of austenitic and martensitic phases [2]

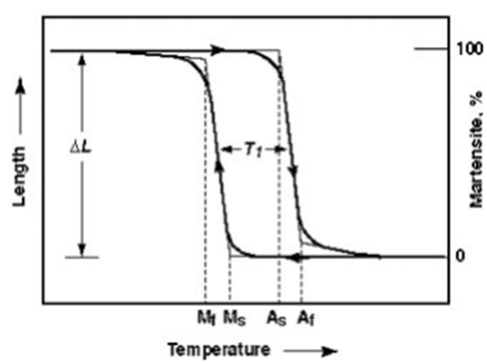

Fig. 2: Lattice structure of austenitic and martensitic phases [3]

The transition between the crystal structures involves a solid phase diffusion-less lattice distortion [1]. Lattice strain generated between grains of the two phases is minimised by the formation of an invariant (undistorted) plane at the interphase boundary. This minimisation of lattice strain is made possible primarily by the generation of 'self-accommodating' twins. This reversible twinning process is the critical part of shape memory behaviours. The self-accommodation process ensures that macroscopic deformation is not generated during the martensitic transformation [2]. Some of the alloy's mechanical and thermal properties also vary between the two phases: for example, Young's modulus, electrical resistivity, thermal conductivity and thermal expansion coefficient [1]. The austenitic structure is relatively hard, whereas the martensitic structure is soft and easily deformable. An explanation for this behaviour will be provided in the next section.

2. THERMOMECHANICAL BEHAVIOUR

The martensitic phase transition exhibits hysteresis, that is, the transition temperatures during cooling and heating are different. As illustrated in Fig. 2 [3], on cooling of austenite, the martensitic start and finish temperatures M_s and M_f are observed. Similarly on reheating, the corresponding temperatures are indicate by the austenitic start and finish temperatures, A_s and A_f, respectively. The presence of hysteresis has a major implication: the dependence of the system's behaviour on its previous state shows that it can exhibit 'memory' like effects.

The deformation behaviour of SMAs is temperature sensitive as shown in Fig. 3 [2]. At lower temperatures the previously twinned martensitic phase undergoes recoverable deformation primarily through de-twinning, since slip motion is not favourable. This gives the martensitic phase its characteristic softness. Thus, yielding of the martensitic phase occurs at the limit of twin deformation, beyond which strain takes place by virtue of typical unrecoverable slip (Fig. 3(a)). However at higher temperatures, when the austenitic phase is more dominant, deformation via slip becomes more prevalent.

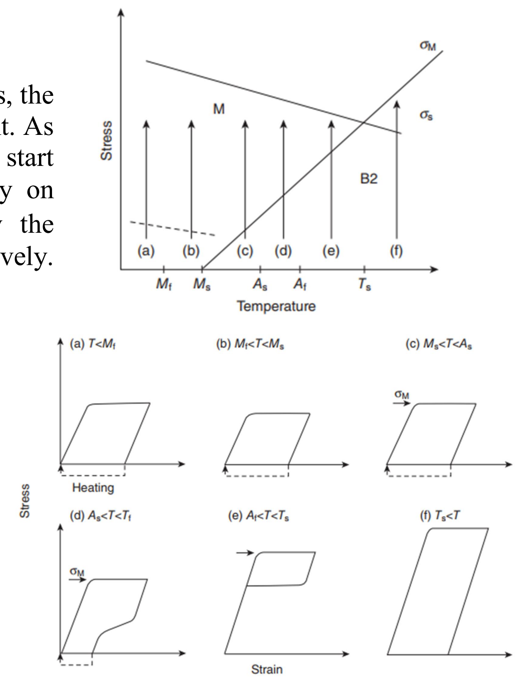

Fig. 3: Stress required to initiate martensitic transformation (σ_M, M) and slip (σ_S, S) as a function of T (top)
Corresponding schematic stress-strain curves at various temperatures (bottom) [2]

The property of superelasticity can be observed in the range $A_f < T < T_S$. The phenomenon occurs due to stress-induced martensitic transformation of the austenitic phase. Since the austenitic phase is the thermodynamically stable phase temperature, the martensite reverts to austenite (since the transformation is reversible). This allows the material to recover high elastic strains (up to 8.5%) [2].

The shape memory effect takes place as follows: When the alloy in the martensitic phase is subjected to a load, it undergoes deformation via de-twinning, which is retained upon removal of load. Upon heating, the austenitic transformation takes place, which restores the original shape. Cooling from this point would again lead to the twinned martensitic structure, with the original shape intact. Thus the original shape is 'memorised'.

The phase transformations and the thermomechanical effects along with the corresponding crystal structures are summarised in Fig. 4 [1].

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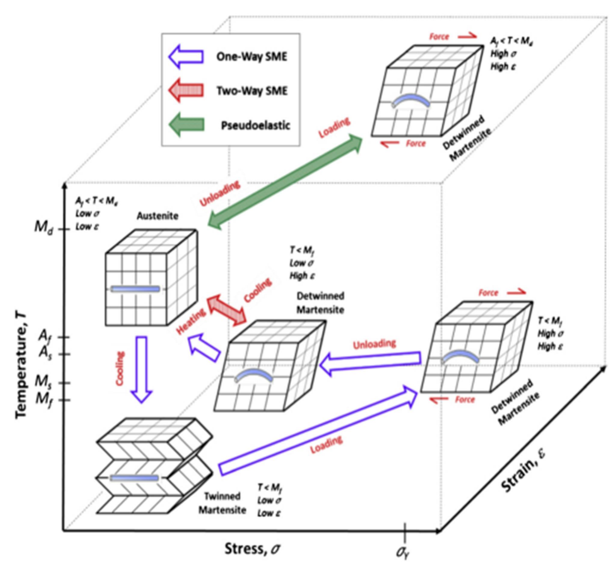

Fig. 4: Shape Memory Behaviour [1]