

Martensitic Transformation of Polycrystalline Shape Memory Alloy

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Abstract: The martensitic transformation (austenite-to-martensite) occurs when the free energy of martensite becomes less than the free energy of austenite at a temperature below a critical temperature T_0 at which the free energies of the two phases are equal. However, the transformation does not begin exactly at T_0 but, in the absence of stress, at a temperature M^{os} (martensite start), which is less than T_0 . The transformation continues to evolve as the temperature is lowered until a temperature denoted M^{of} (martensite finish) is reached. This temperature difference $M^{os} - M^{of}$ is an important factor in characterizing shape memory behavior. When the SMA is heated from the martensitic phase in the absence of stress, the reverse transformation (martensite-to-austenite) begins at the temperature A^{os} (austenite start), and at the temperature A^{of} (austenite finish) the material is fully austenite. The equilibrium temperature T_0 is in the neighborhood of $(M^{os} + A^{of})/2$. The spreading of the cycle ($A^{of} - A^{os}$) is due to stored elastic energy, whereas the hysteresis ($A^{os} - M^{of}$) is associated with the energy dissipated during the transformation. The key characteristic of all SMAs is the occurrence of a martensitic phase transformation. The martensitic transformation is a shear-dominant diffusion less solid-state phase transformation occurring by nucleation and growth of the martensitic phase from a parent austenitic phase.

Keywords: Critical Temperature, Martensitic Phase, Reverse Transformation, Hysteresis, Nucleation and Growth.

I. INTRODUCTION

A shape memory alloy (SMA, smart metal, memory metal, memory alloy, muscle wire, smart alloy) is an alloy that "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated. Martensite (α) forms from austenite (γ) in a diffusionless manner, i.e. there is no variation in composition of the two solid phases during the transformation, and hence the phase transformation can be classified as a solid state diffusionless phase transformation, named martensitic transformation. Due to its practical importance, the martensitic transformation has undergone extensive studies that have led to coining the term "martensitic transformation" as a generic name to describe a solid state diffusionless phase transformation, with specific features, that occurs in a wide variety of materials, such as steels, shape memory alloys as well as in ceramics. Though the martensite formation has been studied quite extensively over the past century, it is still very intriguing due to its complex nature that leaves some questions unanswered.

II. MARTENSITE

A. Morphology

Depending on the alloy composition, martensite forms in the shape of laths, i.e. ruler shaped units, or plates, i.e. lenticular shaped units, as shown in Fig.1. Carbon content of the alloy plays

a major role in determining the martensite morphology. It has been experimentally observed that martensite forms in the shape of laths in low carbon steels and in the shape of plates in high carbon steels.

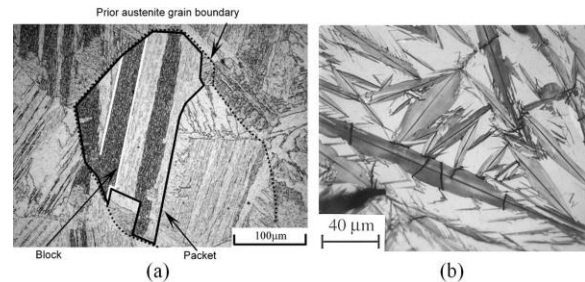


Figure 1: Light optical microscope images of the microstructure of (a) lath martensite in an IF steel with very low carbon content of 0.0049 wt% C (b) plate martensite in Fe-1.86 wt% C alloy.

In the case of lath martensite, several parallel martensite units are formed adjacent to each other. It has been reported that lath martensite forms in blocks and packets in an austenite grain as shown in Fig.1. The strength and toughness of martensitic steels, with lath morphology, are strongly related to packet and block sizes.

In the case of plate martensite, non-parallel martensite units are formed. Moreover, a distinct feature in the case of plate martensite is the midrib, which is reported to be the first forming unit consisting of many transformation twins. On either side of the midrib there exist twinned regions, with some twins that extend from the midrib, and untwinned regions, with dislocations.

B. Transformation

During rapid cooling (quenching) of austenite, athermal martensitic transformation begins at the martensite start temperature (M_s). Thereafter, the volume fraction of martensite increases with decreasing temperature and finally, the transformation is completed on reaching the martensite finish temperature (M_f). In the case of stress assisted martensite, the martensite start temperature at a given stress level σ is termed $M_s\sigma$.

Fig. 2. Shows the microstructural images obtained during an in situ observation, by using laser scanning confocal microscope, of plate martensite formation by means of athermal transformation during rapid quenching of a high carbon steel with a composition of Fe-0.88% C-4.12 % Cr, expressed in mass %. The real time and temperature can be seen in the upper left corner. Slightly above the M_s , one can see untransformed austenite grains in Fig. 2.a. Slightly below the M_s , martensitic transformation initiates in a heterogeneous manner, i.e. nucleation occurs at different sites as can be seen in Fig. 2.b. One can see, in Fig. 2.b, the untransformed austenite grains as well as partly transformed

austenite grains with martensite plates. At a temperature close to M_f , one can see an almost completely transformed steel with complex martensitic microstructure containing several martensite plates oriented in different directions, as shown in Fig. 2.c. Thus it can be understood that the martensite volume fraction increases with decreasing temperature. During rapid cooling, a diffusion controlled transformation of austenite to ferrite, with a very low carbon content, does not occur due to lack of time. However as the temperature is reduced below the T_0 temperature, i.e. the temperature where the Gibbs energies of ferrite and austenite are the same, there exists a thermodynamic driving force available for the formation of ferrite (martensite) with the same composition as that of austenite.

Martensitic transformation leads to the crystallographic transformation of face centered cubic (FCC) austenite in to body centered cubic (BCC) martensite. The carbon atoms that are randomly distributed on the interstitial sites in FCC do not have time to migrate to the BCC in a random manner and hence move in a coordinated motion. This increases the tetragonality of the BCC lattice and thus the carbon containing martensite is of body centered tetragonal (BCT) structure. The tetragonality of martensite increases with increasing carbon content.

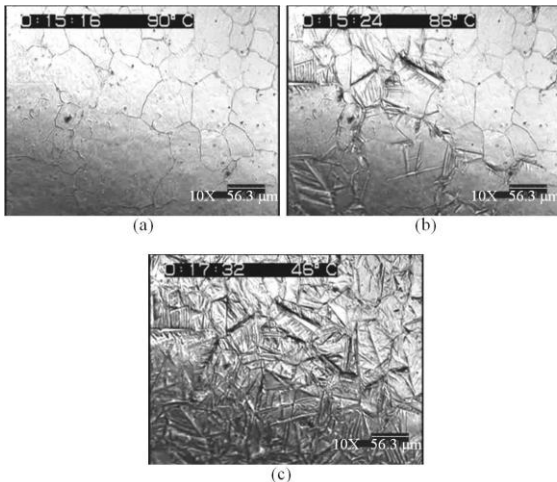


Figure 2.: In situ observation, by using laser scanning confocal microscope, of plate martensite formation in a high carbon steel, where the real transformation time and temperature are marked in the upper left corner. (a) Microstructure at a temperature slightly above M_s . (b) Microstructure at slightly below M_s . (c) Final martensitic microstructure at a temperature close to M_f .

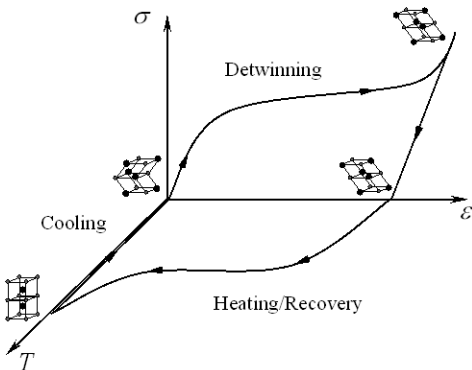


Figure 4. Schematic of a stress-strain-temperature curve showing the shape memory effect.

One-way vs. two-way shape memory

Shape-memory alloys have different shape-memory effects. Two common effects are one-way and two-way shape memory. A schematic of the effects is shown below.

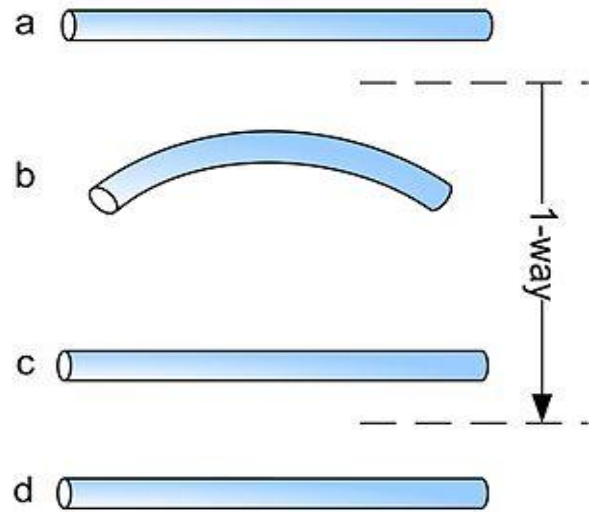


Figure 5: One way shape memory.

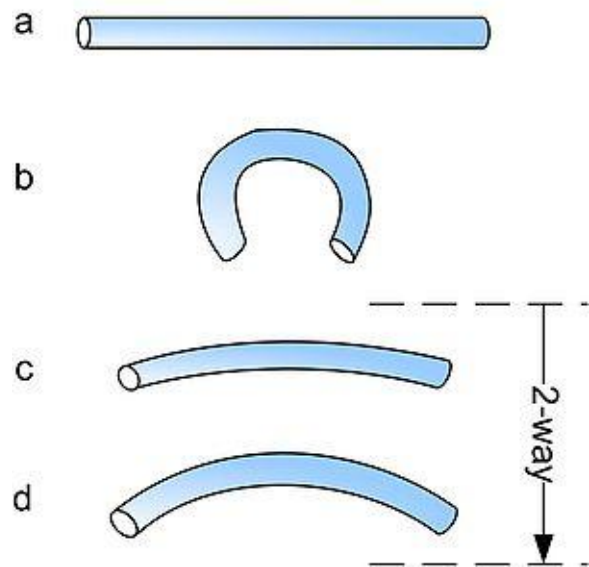


Figure 6: Two way shape memory.

The procedures are very similar: starting from martensite (a), adding a reversible deformation for the one-way effect or severe deformation with an irreversible amount for the two-way (b), heating the sample (c) and cooling it again (d).

III. OBSERVATION

A. Pseudo Elasticity

The *pseudo elastic* behavior of SMAs is associated with recovery of the transformation strain upon unloading and encompasses both *super elastic* and *rubberlike* behavior. The superelastic behavior is observed during loading and unloading above A^{0s} and is associated with stress-induced martensite and reversal to austenite upon unloading. When the loading and unloading of the SMA occurs at a temperature above A^{0s} , partial transformation strain recovery takes place. When the loading and unloading occurs above A^{0f} , full recovery upon unloading takes place.

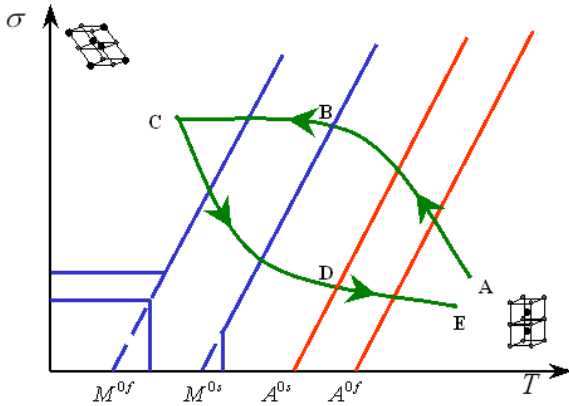


Figure 7. Schematic of a thermo mechanical loading path demonstrating pseudo elastic behavior of SMAs.

Three distinct stages are observed on the uniaxial stress-strain curve representing the superelastic behavior of an SMA. For stresses below M_s , the material behaves in a purely elastic way. As soon as the critical stress is reached, forward transformation (austenite-to-martensite) initiates and stress-induced martensite starts forming.

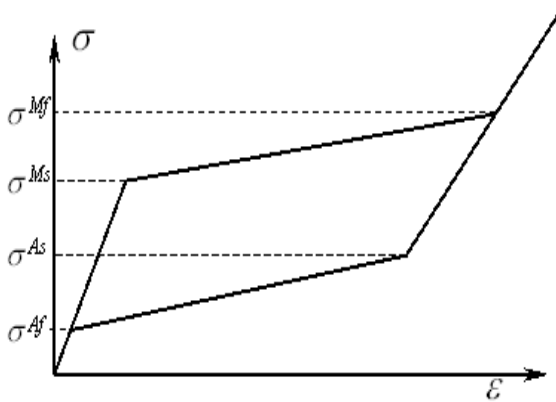


Figure 8. Schematic of the superelastic behavior of SMAs.

Macroscopic transformation strain obtained in that way (Figure 8) is a result of martensite formation and detwinning of the martensitic variants due to the applied load. The transformation strain is several orders of magnitude greater than the thermal strain corresponding to the same temperature difference required for the phase transformation. A hysteresis loop is observed for the cooling/heating cycle as shown in Figure 7 due to the fact that the reverse transformation begins and ends at different temperatures than the forward transformation does.

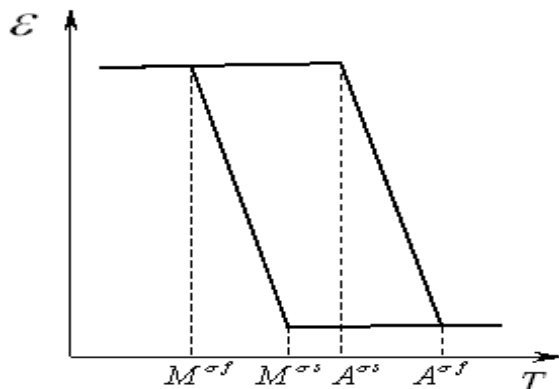


Figure 9: Schematic of isobaric thermally induced transformation behavior of SMAs.

APPLICATIONS

- Aircraft and spacecraft -as vibration dampers, actuator applications.
- Automotive -benefits of SMA over traditionally-used solenoids in this application (lower noise/EMC/weight/form factor/power consumption)
- Robotics-ensures the better movement, very lightweight robots.
- Civil Structures- Intelligent Reinforced Concrete (IRC), which incorporates SMA wires embedded within the concrete.
- Telecommunication-autofocus (AF) actuator for a smartphone.companies working on an optical image stabilisation (OIS) module driven by SMA wires
- Medicine-Optometry, Orthopedic surgery, Dentistry.

PRACTICAL LIMITATIONS

SMA have many advantages over traditional actuators, but do suffer from a series of limitations that may impede practical application.

1. Response time and response symmetry

SMA actuators are typically actuated electrically, where an electric current results in Joule heating. Deactivation typically occurs by free convective heat transfer to the ambient environment. Consequently, SMA actuation is typically asymmetric, with a relatively fast actuation time and a slow deactuation time.

2. Structural fatigue and functional fatigue

SMA is subject to structural fatigue – a failure mode by which cyclic loading results in the initiation and propagation of a crack that eventually results in catastrophic loss of function by fracture.

3. Unintended actuation

SMA actuators are typically actuated electrically by Joule heating. If the SMA is used in an environment where the ambient temperature is uncontrolled, unintentional actuation by ambient heating may occur.

CONCLUDING REMARKS AND FUTURE PROSPECTS

The experimental observations that the martensitic microstructures consist of several twinned martensite variants are observed in the simulated microstructures as well. Autocatalysis, i.e. nucleation of several martensite variants, plastic deformation as well as the non-clamped boundary conditions act as relaxation measures of the stresses developed, due to the martensitic transformation, inside the material. The microstructures obtained in a polycrystalline material indicate that the martensite variants growing in one grain, when impinge up on the adjacent grains, could initiate martensite nucleation in the adjacent grains, where the grain boundaries act as nucleation sites. The study of plastic deformation aspects show that the martensitic microstructure is significantly affected by the plastic relaxation rate, which corresponds to the dislocation mobility and density. The model predicts the initial habit plane of martensite in agreement with the experimental results and predicts that the variants rotate in order to minimize the strain energy. If the rotations of various variants could also be plotted along with the Bain variants shown in the present figures, it might be possible to predict some

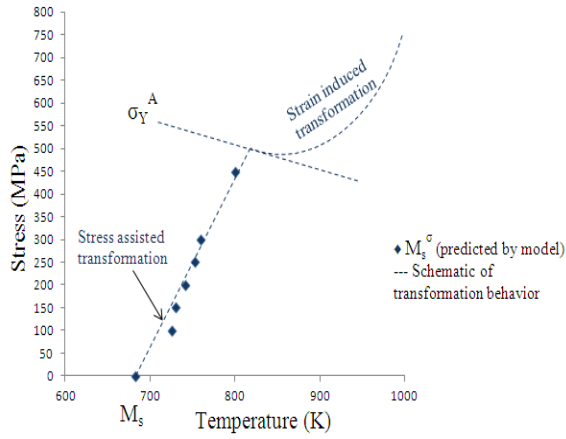


Figure 10: Variation of M_s with externally applied uni-axial tensile stress. more aspects of martensite crystallography and hence this aspect needs an in-depth study.

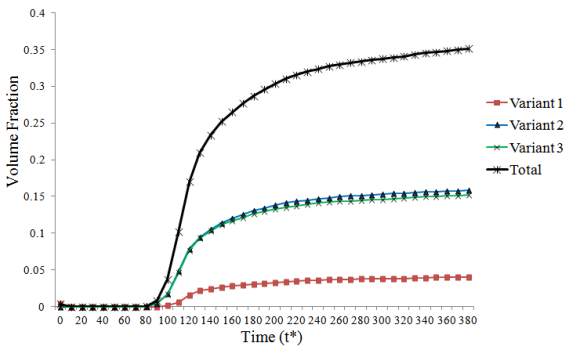


Figure 11: Variation of martensite volume fraction as the microstructure evolves under applied uni-axial tensile stress.

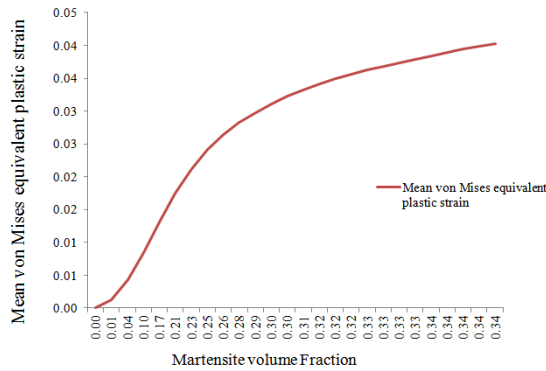


Figure 12: Variation of mean equivalent plastic strain with martensite volume fraction obtained under applied uni-axial tensile stress.

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