The Fatigue Behavior of Shape-Memory Alloys

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Shape-memory alloys have two unique properties: the shape-memory effect (ability of a material to be deformed at a low temperature and then revert to its prior shape upon heating) and superelasticity (the ability of a material to experience large recoverable strains when deformed). Many applications that take advantage of these properties require cyclic deformation, making fatigue behavior an important consideration.

INTRODUCTION

Shape-memory alloys (SMAs) are materials with two unique properties: the shape-memory effect (SME) and superelasticity (SE), also called pseudoelasticity. SME refers to the ability of a material to be deformed at a low temperature and then revert to its prior shape upon heating above a temperature characteristic of the particular alloy. SE is the ability of a material to experience large recoverable strains (up to about 15%) when deformed within a range of temperatures characteristic of the particular alloy.

SME was first observed for Au-Cd alloys in 1951. In 1962, Buehler and co-workers at the U.S. Naval Ordnance Laboratory (NOL) in White Oak, Maryland, discovered SME in nearly equiatomic Ni-Ti alloys, dubbed nitinol (for nickel, titanium, and NOL). They observed that a nitinol wire straightened at high temperature, then cooled and deformed into a coil, would again become straight upon reheating. Similarly, a wire made into a coil at a high temperature, then cooled and straightened, would revert to a coil upon reheating. After this discovery of SME in a commercially viable alloy, research on the SME metallurgy and SMA applications accelerated. Several other alloys were determined to have SME. In particular, copper-based shape-memory alloys (Cu-Zn-Al and Cu-Al-Ni) have attracted much attention because of their lower cost relative to Ni-Ti. However, the only alloys with commercial applications are Ni-Ti and Cu-Zn-Al alloys. These alloys owe their commercial importance to their abilities to recover large amounts of strains or generate a significant amount of force upon shape change.

CHARACTERISTICS

The SME is associated with a martensitic (diffusionless) transformation. While the familiar martensitic transformations in steels are produced by quenching from high temperatures, the transformations in SMAs are thermelastic (i.e., they are reversible upon heating and cooling and occur over a limited temperature range). As with steels, the high-temperature phase is austenite (usually denoted as the $\beta$ phase). In SMAs, the austenitic phase is usually an ordered alloy. Upon cooling, it transforms into the martensitic phase by a twinning-type deformation. The result is an arrangement of alternating platelets with a herringbone pattern, in which the shape changes of the platelet variants tend to cancel any net-shape change (self-accommodation).

The martensitic transformation occurs over some temperature range, and shows a hysteresis effect. Upon cooling from the austenite phase, martensite starts to form at a temperature denoted by $M_s$, and the transformation is completed by the temperature $M_f$. Upon heating from the martensitic phase, austenite starts to form at the temperature $A_s$, and the reverse transformation is completed by the temperature $A_f$. Table I lists a number of alloys that exhibit SMA along with their ranges of transformation temperatures and magnitudes of hysteresis.

The crystallographic transformations associated with the shape-memory effect are shown in Figure 1. Figure 1a is the original crystal in the austenitic phase. Upon cooling to a temperature below $M_s$, the martensitic phase forms, with a change in crystal structure but no net shape change (Figure 1b). Upon heating to a temperature above $A_s$, the martensite reverts to austenite (Figure 1a). Figure 1c and d show the shape changes produced by the deformation of the material when it is in the martensitic phase. Finally, Figure 1e shows that upon heating the deformed martensite to a temperature above $A_f$, the material reverts to austenite with the original shape.

At temperatures sufficiently above $A_f$, the SMA in the austenitic phase behaves as a normal metal, with yielding and plastic flow commencing at a fairly low strain level (curve a in Figure 2). At sufficiently low temperatures, the material behaves as in curve b. The initial modulus in the martensitic phase is smaller than for the austenitic phase. At a low stress level, the favorable martensite variants grow at the expense of less favorable variants, resulting in a large...
amount of strain. A large amount of this strain remains upon unloading, but can be removed with heating, whereby the material reverts to austenite (denoted by the dashed line in curve b of Figure 2). Since the strain is totally removed by heating, the material “remembers” and returns to its original shape, exhibiting the shape-memory effect.

The stress-strain curve c in Figure 2 is obtained at temperatures slightly above $A_y$. At zero load, the material is austenite. Upon loading to point a, the material develops stress-induced martensite (SIM) and undergoes large strains at a constant stress (A-B). During unloading, the SIM reverts to austenite at a lower stress level, and returns completely to austenite at zero load with a complete recovery of strain. This large recoverable strain shown in curve c is characteristic of the SE effect. Similar stress-strain curves are obtained for temperatures between $M_s$ and $A_y$. However, upon unloading the material does not revert completely to austenite, and thus, retains some amount of strain.

**FATIGUE BEHAVIOR**

Since many applications of SMAs require the material to undergo numerous deformation cycles, knowledge of fatigue behavior is essential. Van Humbeeck identified three different types of fatigue that are important for SMAs. The first is the usual failure due to fracture caused by cycling under stresses or strains at a constant temperature. The second is changes in material properties, such as the transformation temperatures and transformation hysteresis because of thermal cycling through the transformation. The third is the degradation of the SME because of mechanical or thermal cycling.

While all three modes of fatigue are important, this article is limited to the usual failure due to fracture of martensitic stresses or strains. The first reported study of fatigue in SMAs appears to be that of Rachinger. He performed a single test on a single crystal of Cu-Al-Ni alloy in plane bending with surface strain limits of ±2% and found a fatigue life of 53,000 cycles. He commented that under such conditions, most materials would fail in 50 cycles or less. Buehler and Wang then reported that “it was possible to load a specimen [of Ni-Ti] up to approximately four times its yield strength, accompanied by considerable specimen deflection during testing, and yet have it run $10^5$ cycles without failure.” Since then many studies have been performed on Ni-Ti and copper-based alloys.

Since Ni-Ti alloys are the most commercially important SMAs, their behavior is discussed first. Of the copper alloys, SMAs based Cu-Zn-Al have been used commercially. Copper-Ni alloys have been developed but not commercialized. Although this article concentrates on polycrystalline materials, several studies have been performed on the fatigue behavior of single crystals, particularly for copper alloys.

### Ni-Ti Alloys

In addition to Buehler and Wang’s early work, Melton and Mercier, McNichols et al., Tobushi et al., Miyazaki et al., and Tablani et al., also performed studies of the fatigue behavior of Ni-Ti. Melton and Mercier performed their experiments with rods 3 mm to 8 mm in diameter; Tablani et al. used tubes with inside diameters of 1 mm and outside diameters of 1.3 mm; and the other authors used wires about 0.8 mm to 1 mm in diameter.

Through slight variations in composition, Melton and Mercier prepared specimens with $M_s$ temperatures ranging from –120°C to 70°C. All testing was performed at room temperature. Tensile stress-strain curves were obtained for $M_s$ ranging from –30°C to 70°C. The specimens with $M_s$ = –30°C and 10°C were initially austenitic, and had plateaus of four percent to six percent in the stress-stain curves, which were due to the formation of the stress-induced martensite. The stress required to induce martensite increases as the difference between the test temperature and $M_s$ increases.

### Table I. Alloys Exhibiting Shape-Memory Effect

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Transformation Composition</th>
<th>Transformation Temp. Range (°C)</th>
<th>Hysteresis (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag-Cd</td>
<td>44/49 at.% Cd</td>
<td>–190 to –50</td>
<td>= 15</td>
</tr>
<tr>
<td>Au-Cd</td>
<td>46.5/50 at.% Cd</td>
<td>30 to 100</td>
<td>= 15</td>
</tr>
<tr>
<td>Cu-Al-Ni</td>
<td>14/14.5 wt.% Al</td>
<td>–140 to 100</td>
<td>= 35</td>
</tr>
<tr>
<td>Cu-Sn</td>
<td>=15 at.% Sn</td>
<td>–120 to 30</td>
<td>—</td>
</tr>
<tr>
<td>Cu-Zn</td>
<td>38.5/41.5 wt.% Zn</td>
<td>–180 to –10</td>
<td>= 10</td>
</tr>
<tr>
<td>Cu-Zn-X</td>
<td>few wt.% X</td>
<td>–180 to 200</td>
<td>= 10</td>
</tr>
<tr>
<td>(X = Si, Sn, Al)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-Ti</td>
<td>18/23 at.% Ti</td>
<td>60 to 100</td>
<td>= 4</td>
</tr>
<tr>
<td>Ni-Al</td>
<td>36/38 at.% Al</td>
<td>–180 to 100</td>
<td>= 10</td>
</tr>
<tr>
<td>Ni-Ti</td>
<td>49/51 at.% Ni</td>
<td>–50 to 110</td>
<td>= 30</td>
</tr>
<tr>
<td>Fe-Pt</td>
<td>= 25 at.% Pt</td>
<td>= –130</td>
<td>= 4</td>
</tr>
<tr>
<td>Mn-Cu</td>
<td>5/35 at.% Cu</td>
<td>–250 to 180</td>
<td>= 25</td>
</tr>
<tr>
<td>Fe-Mn-Si</td>
<td>32 wt.% Mn, 6 wt.% Si</td>
<td>–200 to 150</td>
<td>= 100</td>
</tr>
</tbody>
</table>

**Figure 3. Stress-life (S-N) curves for Ni-Ti.**

Where $A_{el} = CN^{-\beta}$ where $\Delta A_{el}$ is total strain, N is cycles to failure, and C and $\beta$ are constants from the regression. Values of $A_{el}$ are similar for the various alloys and range from 0.16 to 0.22. Melton and Mercier did not report values for C, but they are seen in the figure to vary from 10% to 40%. The total strain range for failure of these alloys at N = 10^6 cycles varies from 4% to 12%; whereas most metals have a total strain range of only 1% at 10^6 cycles. At a given number of cycles to failure, the total strain range was the lowest for $M_s = –120°C$, highest for $M_s = 7.5°C$, and intermediate for both $M_s = –30°C$ and 70°C.

Melton and Mercier recorded the cyclic stress-strain loops to determine the total plastic strain range, $\Delta A_{el}$, which they defined as the total width at zero stress. Total plastic strain ranges and fatigue ductility exponents obtained from linear regressions on the log-log plots are shown in Figure 5a. Most of the values of $\beta$ (negative of the fatigue ductility exponent) shown in Figure 5a are much smaller than those of 0.5 to 0.7 observed for other metals. The one exception is $\beta = 0.43$ for the alloy with $M_s = –120°C$, which would remain fully austenitic and behave as a normal metal.

Melton and Mercier assumed that the total strain range ($\Delta A_{el}$) could be considered as a superposition of an elastic strain ($\Delta A_{el}$), a plastic strain ($\Delta A_{el}$), and a pseudoelastic strain ($\Delta A_{el}$). Values of $\Delta A_{el}$ computed as the quotient of

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