UNIQUE BEHAVIORS OF THE SUPERELASTIC SHAPE MEMORY ALLOY UNDER TENSILE AND COMPRESSIVE LOADING

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Abstract This study deals with the behaviors of the superelastic shape memory alloy (SMA) for large deformation via mechanical loading. Most of the applications and/or, researches on this unique functional material have been mainly centered to its property of superelsaticity, that is, the ability to recover the original shape from the deformed state when the mechanical load, which causes the deformation, is withdrawn. Besides this unique property, however, the peculiar stress-strain curves beyond the stress-induced martensitic transformation (SIMT) region also need careful attention with the view of investigating on the large deformation of the structural elements made of the same material. With this perspective, the behaviors of the superelastic SMA rods have been studied under tensile and compressive loadings for large strains and compared with those of Al and SUS304 rods under similar test conditions. In this work several experiments were carried out to demonstrate a few unique phenomena for the superelastic SMA rods that are absent in the Al and SUS304 rods. The test results are discussed and explained.

Keyword: Shape memory alloy, stress-induced martensitic transformation

INTRODUCTION

Shape memory alloys (SMA) are often used as actuators and sensors for active or passive control purposes in the field of smart materials and structures. Since its discovery researchers have been reporting a number of unique phenomena shown by SMA [Rahman, 2001]. In general, the SMA, also termed as functional material, shows two unique capabilities, that is, shape memory effect (SME) and superelasticity (SE) that are absent in the traditional materials. Both, SME and SE largely depend on the solid-solid, diffusionless phase transformation process known as martensitic transformation (MT) from a crystallographically more ordered parent phase (austenite) to a crystallographically less ordered product phase (martensite) [Brinson, 1993; Rahman, 2001; Auricchio and Sacco, 1997; Otsuka and Wayman, 1998].

The phase transformation (from austenite to martensite or vice versa) is typically marked by four transition temperatures, named as martensite finish (M_f), martensite start (M_s), austenite start (A_s) and austenite finish (A_f). Because of superelasticity (SE), some shape memory alloys can recover large strains (on the order of 10%). To explain SE, consider the case when the SMA that has been entirely in the parent phase ($T>A_f$) is mechanically loaded. From Thermodynamics, there is a critical stress at which the crystal phase transformation from austenite to martensite can be induced. Consequently, martensite is formed due to the applied stress. During unloading, because of instability of the martensite at this temperature in the absence of stress, again at a critical stress, the reverse phase transformation (from the SIM phase to the parent austenite phase) starts. When it is complete, SMA returns to its parent phase (Brinson, 1993; Rahman, 2001) and recovers large strain. The complete loading-unloading cycle shows a typical hysteresis (Fig. 1).

Superelastic SMA is being used as dampers in the structures. It is also used in medical applications. For instance, orthodontic wires, self-expanding micro-structures in the treatment of hollow organ or duct-system occlusions. Applications of the superelastic SMA also includes antenna of portable phones, headband or headphones and eyeglass frames. They are also used to retain the shape of the shoes for comfort [Otsuka and Wayman, 1998]. Besides these applications, extensive studies are reported in the literature mostly on the theoretical constitutive modelling for the superelasticity [Rahman, 2001].

This study discusses a few important phenomena that were observed during the tensile, compressive and torsional loading of the superelastic SMA.

EXPERIMENTAL DETAILS

The materials, configurations and conditions used in this experiment are as follows. Material: superelastic SMA (Ti49.3 at% Ni50.2at% V0.5at%). Diameter of the test specimens and the A_f were 2 mm and -3^{0}C, respectively. Room temperature range was 23^{0}C- 30^{0}C.

As a result, the SMA exists in the parent austenite phase. The Instron machine was used and the speed of the cross-head during experiment was 2 mm/min. To avoid any chance of buckling, the gage length for the pure compressive test should be less than thrice the diameter of the specimen [Johnson, 1972]. Therefore, gage lengths for the specimens were set as 100mm, and 4.5mm for the tensile and compressive tests, respectively. Of course, different specimens were used for those tests.

RESULTS AND DISCUSSIONS

The moduli of elasticity in tension (in this case, strains were simultaneously measured by sensitive strain gages) were found to be 210 GPa, 70GPa and 65 GPa for the SUS304, Al and the superelastic SMA, respectively. The tensile test results for too large strains (till fracture) are shown in Fig. 2. As can be seen, after the distinct plateau, the strength increases significantly for the SMA and exceeds the strength for the SUS304. Obviously, the plateau in the stress-strain curve represents the SIMT for the SMA. The SIMT is initiated when approximately 1.2% strain is exceeded. Tensile test results are summarized in Table 1.

The following important points were observed from the fractured part of the superelastic SMA after the tensile tests leading to fracture: (1) Necking, or reduction of diameter is the least compared to Al and SUS304 rods. (2) The fractured surfaces are rather flat though it represents cup-cone type failure. (3) If the loading continues until fracture, the SMA can store huge amount of strain energy (Fig. 2). Consequently, when fractured, the stored energy is released in the form of sound, flash of light and smoke. On the contrary, only sound is heard when the SUS304 or Al rods are fractured (Table 1). (4) Soon after fracture, the superelastic SMA elastically contracts and recovers 14.7% strain. Apparently, this huge strain recovery (nine times more compared to Al and SUS304 rods) even after fracture is a unique feature of the superelastic SMA.

Table –1 Tensile test results

Material	[1]Total strain (%)	[2]Net strain (%)	[3]Strain recovery (%)	Incidences observed during fracture
SMA	28.7	14.0	14.7	Sound, **flash** and **smoke**
SUS304	18.6	17.0	1.6	Sound
Al	9.6	8.0	1.6	Sound

[1]Total elongation immediately before fracture from Fig. 2
[2]Total elongation (plastic strain) after fracture
[3]Elastic strain recovered

It is noteworthy from Fig.2, the tensile tests that Al rod has the lowest yield strength, while for large strains after the SIMT the SMA rod can carry the highest load. Unlike the superelastic SMA, both the Al and SUS304 exhibit more or less the similar nature of stress-strain curves in compression and tension. On the other hand, it is a well-known fact that the behaviors of the Nitinol SMA in tension and compression are very much different for superelasticity [Orgeas and Favier 1995; Raniecki and Lexcellent 1998]. It was concluded that that though the same martensitic fraction is formed during tension and compression, the orientation of the martensitic variants is more efficient in tension than in compression, which accounts for the above asymmetry. Experimental results from the current study also verify the fact that the compressive strength of the superelastic SMA is significantly higher than its tensile strength particularly for large strains (Fig. 2). Unlike the tensile stress-strain curve, there is no distinct plateau for a particular range of strains. It appears from the compressive stress-strain curve, the SIMT process is indicated by a slight change in slope of the stress-strain curve.

A few unique and important behaviors of the columns and shafts made of the of the same superelastic SMA materials under different types of compressive and torsional loading with different unsupported lengths has been reported by Rahman [2001]. It is found that, if the angle of twist is not too large, because of small residual strain, the superelastic SMA shafts make a much narrower hysteresis than that of the SUS304 shafts under loading-reverse loading cycles. Interestingly, the torsional stiffness of the superelastic SMA increases nonlinearly and exceeds that of the SUS304 [Rahman, 2001].

It should be noted here that strains were measured directly from the Instron machine reading, for Figs. 2-3. Therefore, more accurate values of the strains are possible for Table 1 and the Figs. 2-3 if the strain gage (or other sensitive device) could be used.

Fig.3 shows the unloading curve in tension. As can be seen, the SIMT starts and finishes for approximately 1.2% and 6.5% strains, respectively. When unloaded from a strain of 8.5%, the SMA recovers the shape by a nonlinear hysteresis. The residual strain is about 0.5%.

CONCLUSIONS

Mechanical behaviors of the superelastic SMA rods have been studied under tensile and compressive loadings for large strains and compared with those of Al and SUS304 rods under similar test conditions. As found, for large strains the strength of the SMA increases nonlinearly and exceeds that of the SUS304. The superelastic SMA can store huge strain energy for too large strains. When fractured, the stored energy is released the form of distinct flash of light, smoke and sound. The fractured specimens also exhibit unusually high elastic strain recovery. Among others, unlike the SUS304 and Al, the superelastic SMA exhibits significantly high strength in compression than in tension. The presented results reveal the fact that besides superelasticity, SMA also possesses high strength that could be exploited for useful engineering applications.

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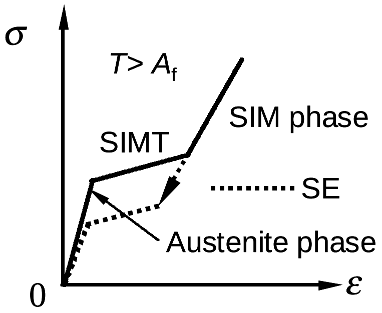

Fig. 1 Idealized stress-strain curve and SE

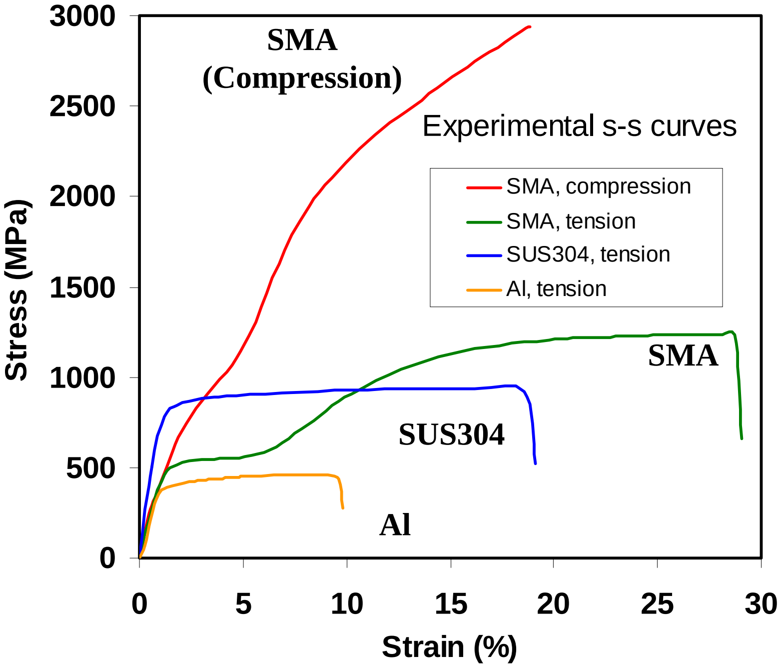

Fig. 2 Tensile stress-strain curves for the AL, SUS304 specimens and tensile and compressive stress-strain curves for the SMA specimens

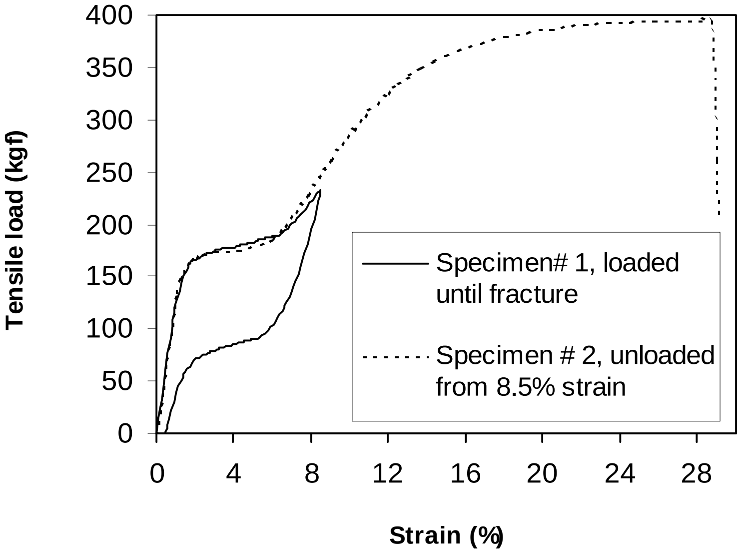

Fig. 3 Test of superelasticity of the SMA rods in tension