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EFFECT OF HEAT TREATMENT ON THE RECOVERY STRESSES GENERATED BY SUPER-ELASTIC NITI SHAPE MEMORY ALLOY WIRES

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ABSTRACT

This paper presents a study of the effect of heat treatment on the maximum and minimum recovery stresses generated by super-elastic SMA wires. The experimental work involved subjecting raw SMA wires to different heat-treatment temperatures using a muffle furnace immediately followed by water quenching. Recovery stress tests were then conducted on the pre-strained heat-treated SMA wires using a 50 kN tensile machine to determine the maximum and minimum recovery stresses generated by the SMA wires. The experimental work also included conducting tensile tests on the SMA wires using a 100 kN tensile machine to determine their mechanical properties. The findings of this study indicate that the maximum recovery stresses produced by heat-treated SMA wires increase with increasing heat treatment temperature, while the minimum recovery stresses (residual stresses) produced by heat-treated SMA wires increase with increasing heat treatment temperature up to 350°C, then decrease at 400°C. The recovery stresses generated by NiTi SMA wires can be used to provide pre-stressing or confinement in concrete and steel structures.

KEYWORDS

Smart material, SMA (shape memory alloy), recovery stress, SME (shape memory effect), SE (super-elasticity), SIM (stress-induced Martensite).

INTRODUCTION

Nickel-titanium (NiTi) shape memory alloys (SMAs) are unique intelligent alloys that are mainly composed of two elements, nickel and titanium. They have the ability to recover their original shape after being subjected to large deformations, either by the shape memory effect (SME) or super-elasticity (SE). If they are restrained during the recovery process, they have the ability to generate large recovery stresses. Shape memory alloys exist in two phases, the first phase being called Martensite, which is the low temperature phase. In this phase the alloy is soft and easily deformable. The second phase is called Austenite, which is the stronger phase and occurs at high temperatures. SMAs are mostly recognised for their two amazing shape-recovery characteristics. These are the shape memory effect (SME) and super-elasticity (SE) and these characteristics are mainly dependent on the material properties and the external conditions. The SME of SMAs occurs when the material is deformed at low temperature (Martensite phase), and the alloy can be recovered to its original shape by heating it above a specific temperature. In contrast, the SE of SMAs occurs when the material is deformed at high temperature (Austenite phase), and the alloy can be recovered to its original shape by simply removing the applied load.

SMAs have many applications in structural engineering, especially in the rehabilitation of concrete and steel structures. Maji and Negret (1998) investigated the use of SMA wires to provide pre-stressing in concrete members. Andrawes and Shin (2008), Andrawes et al. (2010), and Choi et al. (2008) proposed the use of SMA wires to provide external confinement for reinforced concrete columns. Li et al. (2006a), Li et al. (2006b) and Sakai et al. (2003) presented the use of SMA wires to control cracks in concrete members. For steel structures, Hu et al. (2008) and Ocel et al. (2004) studied the use of super-elastic SMA bars to enhance rotational behaviour at steel beam–column connections. These applications depend either on SME or SE.

The shape memory effect and super-elasticity of NiTi alloy are influenced by the alloy’s chemical composition, the annealing temperature and the history of its mechanical deformation. Therefore, a mix of cold work followed by a specific annealing temperature is considered to improve the characteristics of a shape memory alloy (Fuentes et al. 2003). Significant attention has been paid to exploring the effect of the annealing process on the properties of NiTi alloys. For example, Yoon and Yeo (2004) investigated the effect of heat treatment conditions, including both heat-treatment duration and temperature, on the transformation temperatures and thermo-mechanical properties of Nitinol wires (54.5Ni–45.5Ti wt%). Eggeler et al. (2005) studied the effect of ageing of a NiTi alloy at 450°C on its transformation temperatures using differential scanning calorimetry (DSC) and microscopy. They found that, in general, the transformation temperatures increase as the ageing time increases. The behaviour of super-elastic Ti–50.85Ni (wt%) shape memory alloy with different annealing temperatures has been reported experimentally (Huang and Liu 2001). A study conducted by Sadiq et al. (2010) investigated the effect of heat treatment on the maximum recovery stresses generated by the SMAs at the highest activating temperature. These researchers recommended that, in order to produce the desired thermo-mechanical properties in the alloy for applications that exploit the shape memory effect, it should be annealed at temperatures below 450°C.

Substantial efforts have been directed to studying the effects of heat treatment on the thermo-mechanical properties and the micro-structures of NiTi alloys and the maximum recovery stresses generated by SMAs. However, to date no attention has been dedicated to the investigation of the influence of heat treatment on the minimum recovery stresses (residual stresses) generated by SMAs at room temperature. This objective of this paper is to report on an experimental study of the effect of heat treatment on the mechanical properties at room temperature and, in particular, on the minimum recovery stress of superelastic NiTi alloy. The residual stresses of SMAs can be used in structural applications to provide pre-stressing or confinement in both concrete and steel structures.

EXPERIMENTAL PROGRAM

Tensile Tests of SMA Wires

Super-elastic SMA wires 1.00 mm in diameter were used to determine its stress-strain behaviour. The tensile tests were conducted according to the ASTM standard (ASTM F2516). Raw SMA wires were subjected to different heat-treatment temperatures (200^{o}C-400^{o}C) using a muffle furnace for 1 hour, immediately followed by water quenching. The wires were then sandblasted to remove the oxide residue and increase their surface roughness. The SMA wires were gripped using specially machined spool grips attached to a 100 kN tensile machine. Local strain measurement via a non-contact video extensometer was used to measure the strain during the tensile testing. The video extensometer observes the distance increase between two visible markers. To achieve this purpose, small diameter (around 3-5 mm) expanded polystyrene spheres (normally used for packing purposes) were affixed to the wire specimen before attaching it to the grips. Tensile tests to failure were conducted at a strain rate of 3.33×10^{-4}/s. The complete set-up of the SMA wire tensile test is shown in Figure 1.

Recovery Stress Tests of SMA Wires

Super-elastic SMA wire 1.00 mm in diameter (the same wire used in the tensile tests) was used in these tests to determine the recovery stress. According to the information provided by the manufacturer (Memry Corporation), the Austenite start temperature (A_s) of the super-elastic (fully annealed as per ASTM F2004) SMA wires is -13/-10 ℃ and the Austenite finish temperature (A_f) is on average 15 ℃ warmer than A_s. The chemistry of the super-elastic SMA wires is specified according to the ASTM standard (ASTM F2063). The same heat treatment procedures used for the SMA wires in the tensile tests were used for treating the SMA wires used in these tests. The SMA wires were sandblasted to remove the oxide residue and increase their surface roughness. Special grips were then attached to both ends of the wire and this set-up was attached to a 50 kN tensile machine, as shown in Figure 2. Before conducting the recovery tests on the SMA wires, they were mechanically pre-strained using the 50 kN tensile machine to a maximum strain of 6% - 8%. The heat required to activate the SMA wire was provided by electrical resistivity (Joule heating) using a power supply and a simple electrical circuit. A thermocouple was attached to the middle of the SMA wire to measure the temperature during the test with the help of a computerised data logger. The complete set-up of the test is shown in Figure 2. The test was started by switching on the power supply to activate the SMA wire, the data logger to record the temperature and the 50 kN testing machine software to record the recovery stress generated by the SMA wire. All these steps were started simultaneously.

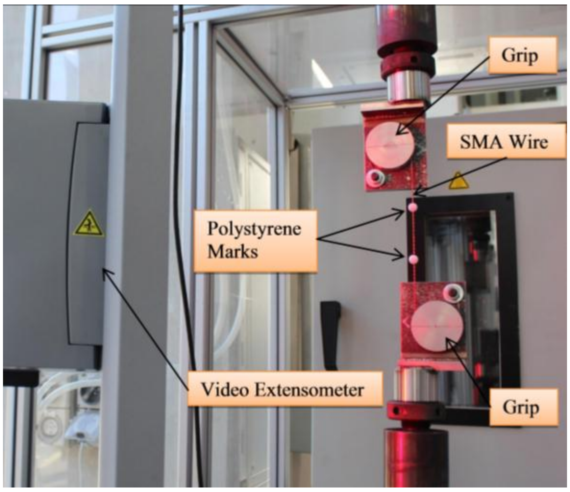

Figure 1. Experimental set-up for the tensile testing of SMA wire

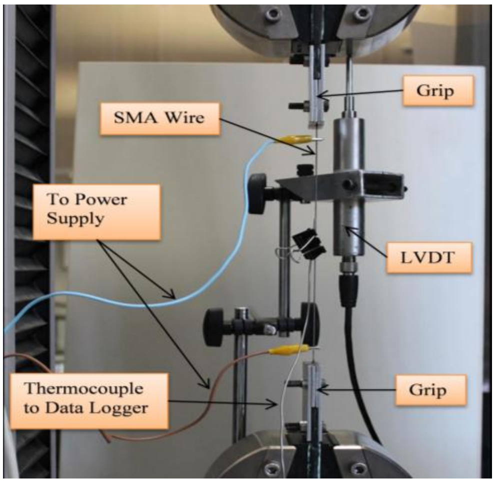

Figure 2. Experimental set-up for recovery stress testing of SMA wire

RESULTS AND DISCUSSION

In the first part of the experimental program, tensile tests were conducted on both the as-received and the heat-treated super-elastic SMA wires to determine the effect of the heat treatment process on the mechanical properties and the stress-strain evolution of the SMA wires. The results of the tensile tests are presented in Figure 3. From the figure, it can be seen that with the increase in the heat-treating temperature there is a considerable change in the proportional limit and the stress-strain curve shape for the heat-treated SMA wire compared to the as-received wire, indicating that the raw super-elastic SMA wire started to show some transformation from the Austenite phase to the Martensite phase until reaching full transformation at a heat-treatment temperature of 400^{o}C. This type of transformation is called stress-induced Martensite (SIM). It can also be seen that with increasing heat-treatment temperature there is a slight increase in the ultimate tensile strength up to a temperature of 350^{o}C and a decrease at a temperature of 400^{o}C. In addition, a significant increase is noticed in the total elongation to rupture up to a heat-treatment temperature of 350^{o}C and a slight decrease at a heat-treatment temperature of 400^{o}C.

In the second part of the experimental study, recovery stress tests were conducted on heat-treated superelastic SMA wires to determine the effect of the heat treatment process on the maximum and minimum recovery stresses of the wires. The SMA wires were subjected to mechanical training cycles using the 50 kN tensile machine and then the recovery stress tests were performed. The mechanical training cycles to produce 8% pre-straining on the stress-strain curve at room temperature for the wires heat-treated at 350°C are shown in Figure 4. The evolution of the recovery stresses with the SMA temperature for the wires heat-treated at 350°C is depicted in Figure 5. It is worth noting that the maximum recovery stress is recorded at the maximum temperature attained during the heating cycle and the minimum recovery stress is recorded after cooling the SMA wire to room temperature, as shown in Figure 5. The results of the maximum and minimum recovery stresses generated from the NiTi wires heat-treated at different temperatures are presented in Figure 6. Figure 6 shows that the maximum recovery stresses produced by the heat-treated SMA wires increase with increasing heat-treatment temperature, while the minimum recovery stresses (residual stresses) produced by the heat-treated SMA wires increase with increasing heat-treatment temperature up to a temperature of 350°C and then decrease at a temperature of 400°C. More precisely, it can be observed that a significant change in maximum recovery stresses occurs between heat-treatment temperatures of 250°C and 300°C. The same behaviour is noticed for the minimum recovery stresses.

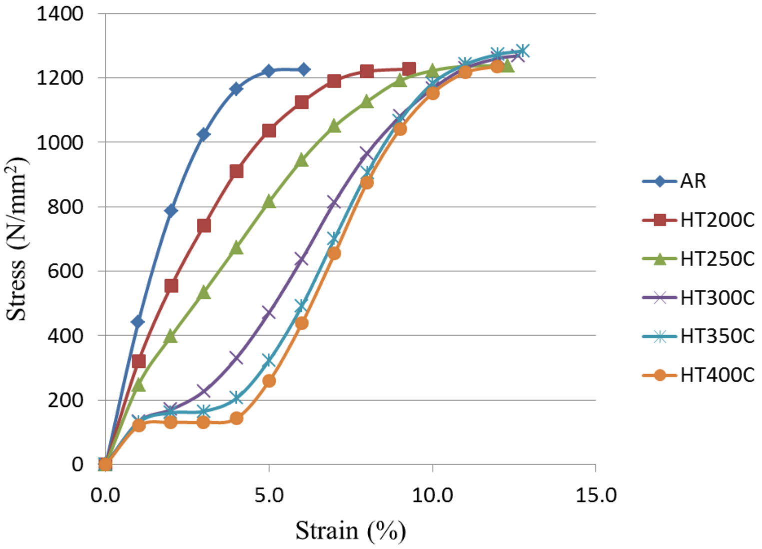

Figure 3. Stress-strain relationships of as-received and heat-treated super-elastic SMA wires

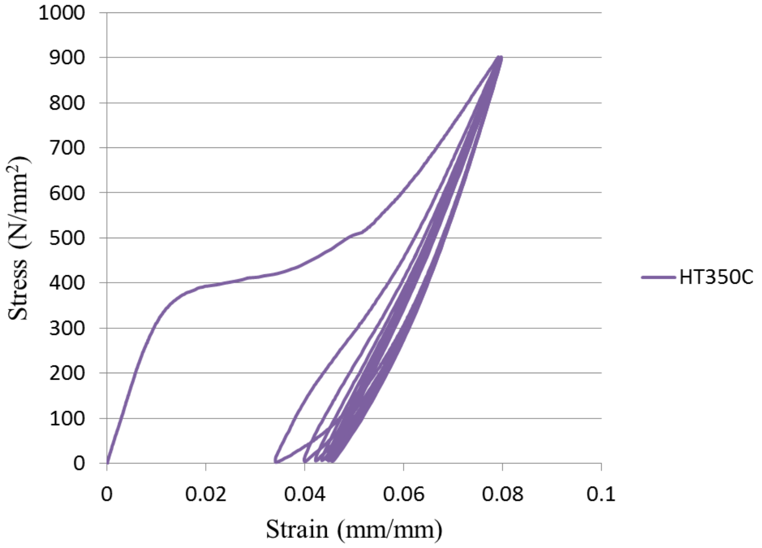

Figure 4. Mechanical training cycles for SMA wires heat-treated at 350°C

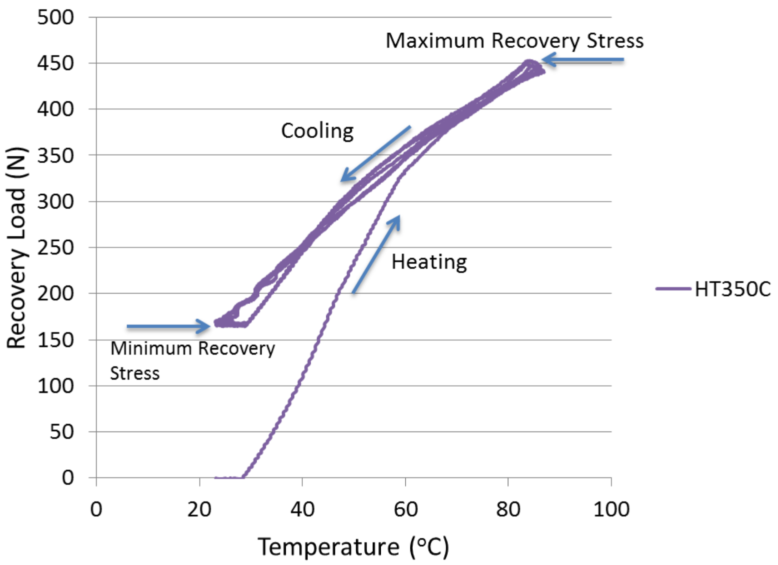

Figure 5. Recovery stresses for SMA wires heat-treated at 350^{o}C

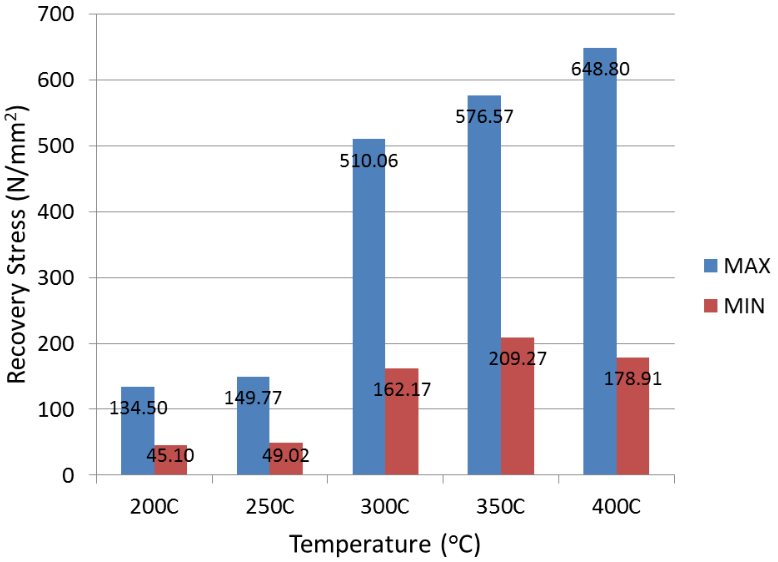

Figure 6. Maximum and minimum recovery stresses of heat-treated super-elastic SMA wires

CONCLUSION

In this study, tensile tests were performed on both as-received and heat-treated super-elastic SMA wires to determine the influence of heat treatment on the mechanical properties and the stress-strain relationship of the SMA wires. In addition, recovery stress tests were conducted on the heat-treated superelastic SMA wires to determine the effect of heat treatment on the maximum and minimum recovery stresses of the wires. It was found that the mechanical properties and the shape of the stress-strain relationship curves for the SMA wires are significantly affected by the heat treatment process. It was also found that the maximum recovery stresses generated by the heat-treated SMA wires increase with increasing heat treatment temperature, while the minimum recovery stress increases up to a heat-treatment temperature of 350^{o}C then decreases at a temperature of 400^{o}C. The recovery stresses generated by the NiTi SMA wire studied in this work can be used to provide pre-stressing or confinement in concrete and steel structures after exposing it to a heat-treatment temperature of 350°C.

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