ESOMAT 2009, 06038 (2009)
DOI:10.1051/esomat/200906038

Phase transformation fronts propagation during the stress induced martensitic transformation at impact strain rates in NiTi shape memory alloy wires

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Abstract. Propagation of phase transformation fronts during the stress induced martensitic (SIM) transformation at impact strain rates, on the order of 10 s^{-1}, was observed *in situ* by measuring changes in infrared radiation on the surface of superelastic NiTi wires. The exothermic/endothermic character of the forward/reverse SIM transformation changes the local temperature making visible the nucleation and propagation of phase transformation fronts. The nucleation during forward SIM transformation usually occurs at both ends of the sample near the grips, where stress concentrations are unavoidable. During unloading, nucleation of the reverse SIM transformation takes place at point where the forward SIM transformation was finished. At impact no more nucleations were observed so that only the phase transformation fronts arising from the mentioned nucleations appear. In the non-transformed zone, the temperature remains similar to that observed for the test in which only the elastic deformation of the austenitic phase occurs. This feature shows that the SIM transformation at impact strain rates is inhomogeneous and, similarly to that observed at very low strain rates, lower than 10^{-4} s^{-1}, when the deformation may be considered as an isothermal process and the temperature in the sample remains almost constant, no multiple transformation fronts appear as is observed when strain rate is on the order of 10^{-4}-10^{-2} s^{-1}. For specimens cycled at impact, the nucleation at the beginning of the SIM transformation occurs at several locations and during the deformation more nucleation points arise since the stress necessary to initiate another nucleations is lower than necessary to continue the propagation of the active fronts. These locations are similar for different cycles showing that they do not arise by chance, but rather because there are locations more favourable for the nucleation.

1. Introduction

Recently, shape memory alloys (SMA) are becoming increasingly important for impact applications due to their large recoverable strains and high capacity to dissipate energy. For instance, these alloys are highly attractive for energy absorption/storage, impact damping or seismic protection [1-3]. Nevertheless, the thermomechanical behaviour of these alloys at impact strain rates, on the order 1-10^2 s^{-1}, is not yet well known and only a few works deal with the dynamics of propagating phase boundaries at impact strain rates [4], while the maximum strain rate at which the transformation fronts have been observed via infrared radiation has been 10^{-2} s^{-1} [5,6]. In the present work, the phase transformation fronts at impact strain rates, on the order 10 s^{-1}, were observed on the surface of NiTi wires via thermographic observations. The stress-strain response was simultaneously registered with the thermographic observations in order to link the evolution of the transformation fronts with the mechanical behaviour.

2. Experimental procedure

Infrared thermographic pictures were taken at a frame rate of 1250 Hz with a high speed thermographic camera Flir Titanium 550M during tensile deformation of NiTi wires at impact strain rates. The impact tests were carried out with an instrumented tensile impact device. The whole experimental set-up is shown in figure 1. It consists on an impactor which deforms the sample by hitting a mobile grip at which the sample is attached. The impact force is measured by a piezoelectric sensor ICP® quartz force ring attached to the other grip which is fixed. The measurement of the deformation during the impact was carried out with a laser–based noncontacting measurement equipment Polytec OFV–505. More detailed information of the instrumented tensile impact test applied to SMA wires may be found in [7]. During deformation, simultaneous measurements of infrared

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radiation, force and deformation were performed so that the transformation fronts may be visible while it is known the stress-stain state. For each test of the experimental work, a commercially available NiTi wire, ref. NT09, purchased from (AMT) @medical technologies, of 80 mm in free length and 0.5 in diameter was used. The transformation temperatures of the sample are below zero showing superelastic behaviour at room temperature. The tensile-impact tests were carried out at room temperature with an impactor mass of 1.098 kg. They were performed at different impact energies by varying the impact velocity from 0.77 to 1 m/s in order to achieve different maximum strains keeping the strain rate during the test on the order of $10\ s^{-1}$.

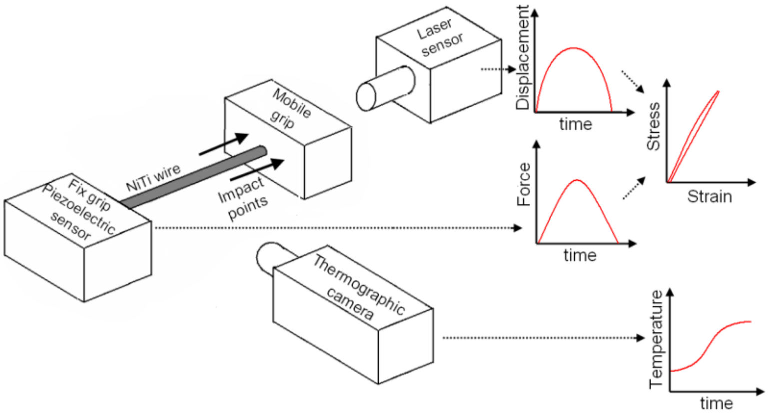
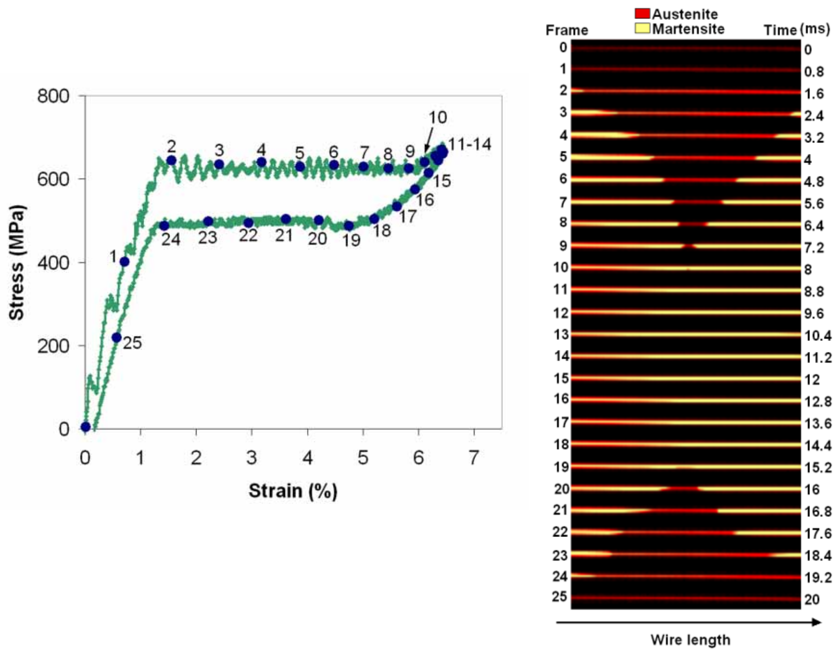


Fig. 1. Schematic diagram of the experimental set-up.

3. Results

At impact strain rates, the nucleation of the forward stress induced martensitic (SIM) transformation occurs at the site having the highest stress, which is usually at the grips where stress concentrations are unavoidable. Once the nucleation has occurred, the transformation fronts from the austenitic to the martensitic phase moves towards the middle of the sample, figure 2b. No more nucleations were observed during the forward SIM transformation at impact strain rates, and in the zone of the sample where the front does not go through, the temperature remains similar to that observed for the test in which only the elastic deformation of the austenitic phase occurs. During unloading, the nucleation of the reverse SIM transformation takes place at point where the forward transformation was finished. The confluence of the forward transformation fronts originates a discontinuity in the crystal lattice which is favourable for the nucleation of reverse SIM transformation.



a) b)

Fig. 2. NiTi wire phase transformation fronts evolution during the complete martensitic transformation (ε=6.5%), induced at impact strain rate ($10\ s^{-1}$). a) Stress-strain curve. b) Thermographic pictures taken every 0.8 ms.

This feature shows that the SIM transformation at impact strain rates is inhomogeneous, similarly to that observed at very low strain rates, 10^{-4} s^{-1} or lower [8,9], and no multiple transformation fronts appear as is observed when strain rate is on the order of 10^{-4}-10^{-2} s^{-1} [5]. It is well known that when the deformation is performed at very low strain rates, there is enough time to allow all the transformation heat to be exchanged with the surroundings being the temperature in the sample almost constant. Then, the nucleation only appears at the grips and only one or two fronts appear during SIM transformation [8,9]. Nevertheless when the strain rate is increased, up to 10^{-2} s^{-1}, the number of transformation fronts are multiplied. This occur because at higher strain rates, part of the heat generated during SIM transformation cannot be released to the surroundings and is spent in warming up the transformed zone. This leaves cooler regions in the sample where stress necessary to generate another nucleation is lower than necessary to continue the propagation of the active fronts, so that new nucleations appear. As strain rate is increased, the deformation process is closer to the adiabatic condition, and self-localized heating may be more intense, generating more and more new fronts [5]. Nevertheless, in this work it is shown that this explanation is not valid at impact strain rates since no multiple transformation were observed. This may be due to the fact that at impact, the deformation time is so small, 15-20 ms, that there is not enough time to allow another nucleations to be formed, making it easier to continue with the initial fronts. It seems that at impact, the stress necessary for a new nucleation in the non-transformed zone is higher than necessary to continue the propagation of the previously generated fronts. In order to study in depth this idea another test was performed. A sample was deformed at impact until 4% in strain (around half of the SIM transformation). This deformation cycle was repeated 100 times and the data was recorded for the 1st, 2nd, 50th and 100th cycles, figure 3.

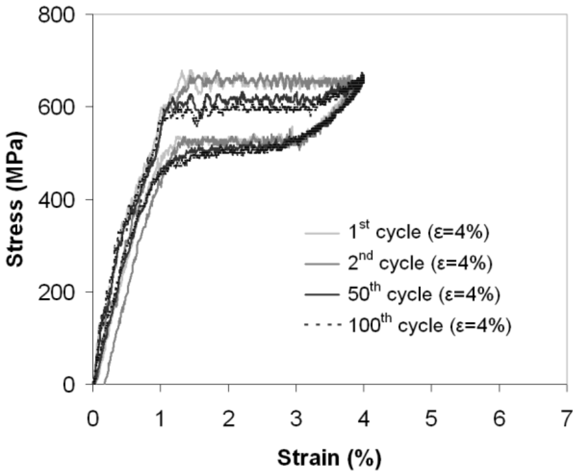
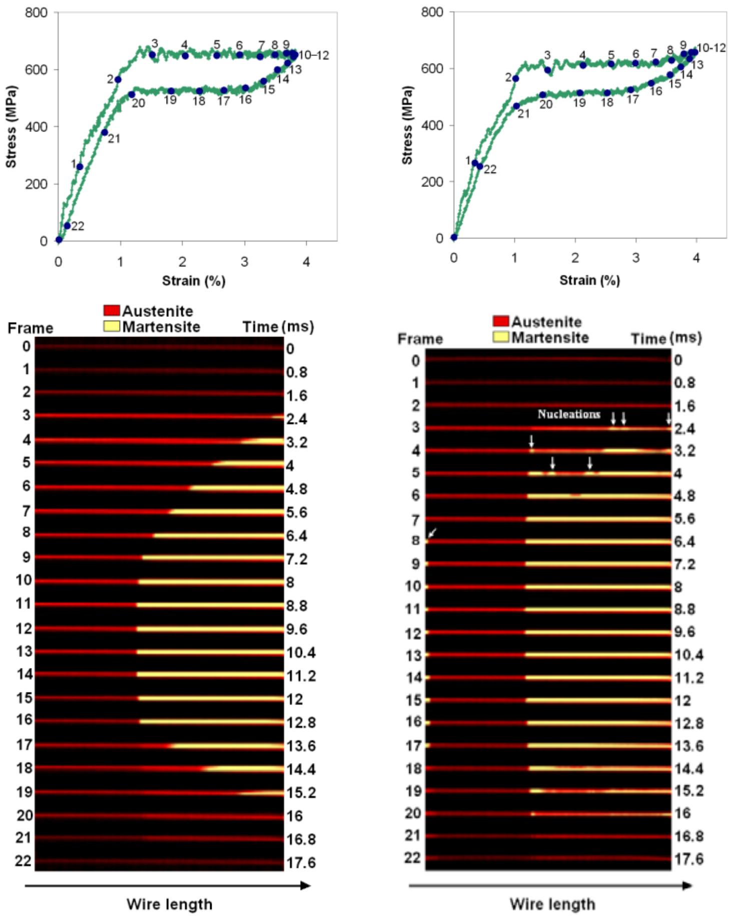


Fig. 3. Stress-strain curves of NiTi deformed up to half of the SIM transformation for several cycles. Strain rate $10^{+1}s^{-1}$.

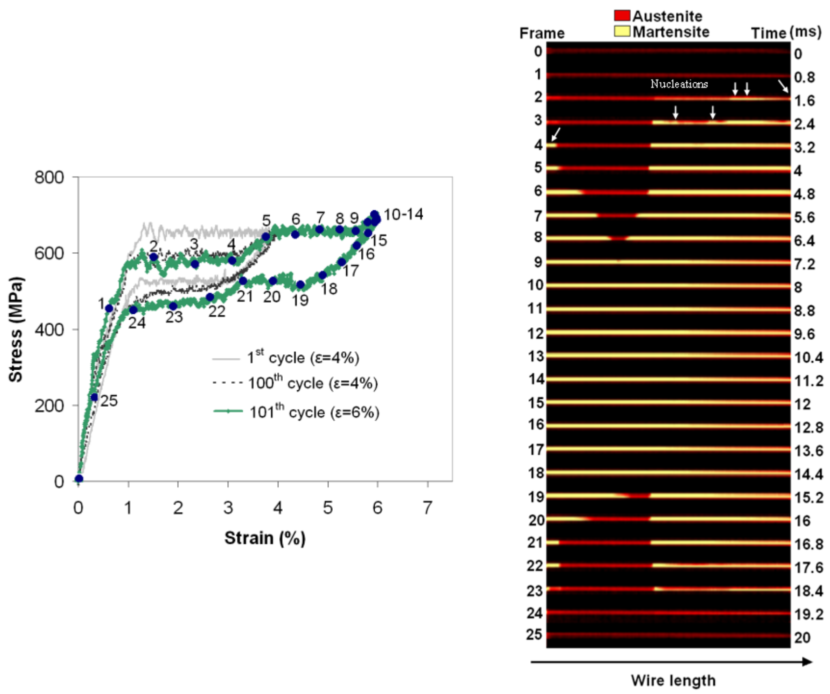
For the first cycle only one propagation front appears, figure 4a, similarly to that occurred for the second cycle. The only nucleation occurs at a grip and propagates approximately until the middle of the sample. Nevertheless, it may be observed from the thermographic pictures of the 50th cycle, figure 4b, that with cycling the nucleation at the beginning of the forward SIM transformation occurs at several points and during the deformation another nucleation points arise. This may be due to the fact that during cycling deformation, small defects arise creating discontinuities in the crystal lattice and local stress fields that may retain certain amount of preferential oriented martensite which assists the generation of new nucleations at those locations during the subsequent transformations. Then, the stress necessary to initiate another nucleation is lower than necessary to continue the propagation of the active fronts, as show the lower transformation stresses during the SIM transformation for the 50th and the 100th cycles, figure 3. The nucleation locations for the 50th and for the 100th cycles are similar showing that the nucleation points do not arise by chance, but rather they arise at locations where the discontinuities in the crystal lattice are more favourable for the SIM nucleation.

With the aim to study what happens in the non-transformed zone, another test was performed. The specimen cycled 100 times up to 4% was deformed at impact until 6% in order to perform the complete SIM transformation, figure 5a. The thermographic pictures show that for the deformation until 4%, several nucleation locations appear similar to those occurred in the 50th cycle shown in figure 4b. Nevertheless, from the 4% to 6% in strain only two fronts propagate, one arising from the grip closer to the non-transformed zone, and another from the previously transformed zone. For the latter strain, multiple fronts do not appear because there is not any defect that may assist a new nucleation. In figure 5a is shown that the multiple nucleations occur since the stress necessary for it is lower than necessary to continue the propagation of the previously active fronts.



a) b)

Fig. 4. NiTi wire phase transformation fronts evolution during the deformation up to half of the SIM transformation at impact strain rate (10 s^{-1}). a) 1st cycle. b) 50th cycle.



a) b)

Fig. 5. NiTi wire phase transformation fronts evolution during complete SIM transformation previously cycles 100 times up to half of the transformation. Strain rate 10 s^{-1}. a) Stress-strain curve. b) Thermographic pictures taken every 0.8 ms.

4. Conclusions

The stress induced martensitic (SIM) transformation at impact strain rates, on the order of 10 s^{-1}, in NiTi wires is inhomogeneous similarly to that observed at very low strain rates, lower than 10^{-4} s^{-1}. The nucleation of the forward SIM transformation occurs at the grips because of the stress concentrations, and the front transformations travel through the sample until complete the SIM transformation. During unloading, nucleation of the reverse SIM transformation takes place at point where the forward SIM transformation was finished. At impact, no more nucleations were observed. When cycling, multiple transformation fronts appear because the movement of the interface austenite/martensite generate defects that may assist the subsequent transformations. Then, the stress necessary to initiate another nucleations is lower than necessary to continue the propagation of the previously active fronts.

Acknowledgements
The authors would like to thank the Basque Government for the financial support (PI2008–07, IE05–150).

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