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Crack micromechanisms in cycled shape memory alloys

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Abstract

Shape memory alloys are more and more used in many industrial, medical and automotive fields due to the ability to recover the initial shape after external loads producing high deformations thanks to the variations of their microstructure due to thermal or mechanical causes. Up to now, many models have been developed in order to describe the mechanical behaviour of SMA but most of them don't take into account the real microstructure.
In this work a traditional equiatomic NiTi SMA has been investigated both in terms of microstructure evaluation and in terms of mechanical cycling behaviour up to degratate the memory ability, obtained at around 100 cycles. The cycling behaviour has been investigated and a model has been proposed to predict the mechanical behaviour and the ability to recover the initial microstructure.
The damaged alloy has been investigated in terms of surface fracture analysis obtained by traditional traction tests in order to investigate the main crack micromechanisms.

Keywords: Additive manufactured lattice core; Composite material skin; Mechanical behaviour

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1. Introduction

Shape memory alloys are a wide class of materials covering metallic alloys and some kinds of polymeric ones, that are able to recover the initial shape also after high values of deformations caused by external mechanical loads (Volpe et al. 2014). Removing the external loads can append two effects (Furgiuele and Maletta 2010):

1) the initial shape will receive immediately without any external other action
2) the initial shape is recovered after heating of the material at a temperature higher than a critical one.

In the first case the material is characterized by a critical temperature lower than environment one and the material is a shape memory characterized by a pseudoelastic effect (Brotzu et al. 2015, Carpinteri et al 2018).

In the second case, the material is classified as a shape memory alloy which needs an external source of energy (the thermal energy) to recover the initial shape (Iacoviello et al 2018).

This is due to the relatively low temperature where the lattice of alloy can change transforming from a stable low-temperature lattice, often named as austenite, to a different lattice named as martensite (Vantadori et al. 2018 and Di Cocco et al. 2018).

The transition temperature value is several orders of magnitude lower than the recrystallization one, allowing to change the microstructure without changing boundaries. It means that the lattice changing doesn't imply any migration of atoms between crystals and the number of crystals is always the same (Berto et al. 2021).

In the last years many studies have been carried out regarding different aspects of the shape memory alloys. For example there are some studies about the behaviour of copper base SMA (Volpe et al. 2014) where the grains are well observable using the metallographic LOM allowing to show the behaviour of the boundaries during the lattice changing. Other studies regarding the nanohardness behaviour of NiTi SMAs (Muller et al 2012) or the fatigue behaviour (Maletta et al 2011 and 2012) showed the influence of the microstructure changing on mechanical behaviour. The interaction of temperature is highlighted in recent work (Sgambitterra et al. 2016), but no more works regarding the quantification of the microstructure change induced by mechanical effect are related to the mechanical behaviour of SMAs.

In the last years Di Cocco et al. 2018 proposed a simple model able to calculate the effective microstructure evolution induced by mechanical loads in cycling tests and successively in Berto et al. 2021 a relationship of effective microstructure and mechanical behaviour has been proposed.

In this work tensile fracture micromechanisms have been analysed in order to evaluate the influence of the cycles on the tensile fracture behaviour of an equiatomic SMA characterised by a pseudoelastic behaviour.

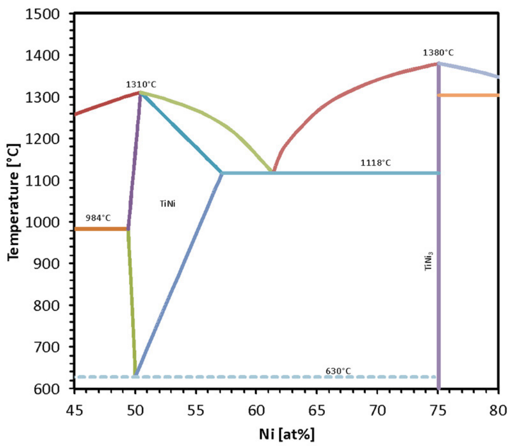


Fig. 1. NiTi Phase diagram.

2. Materials and methods

An equiatomic NiTi alloy characterized by a PE mechanical behavior has been used in order to evaluate the structural modification in low cyclic. The equilibrium state diagram of the investigated alloy is shown in Fig. 1, where a presence of a cross of limit of solution of two different phases is the peculiarity of this alloy. The influence of chemical composition is very strong in terms of mechanical behavior, because weekly differences of Ni or Ti contents change the stability of phases and can modify the memory properties of an alloy.

The thermo mechanical process carried on the investigated material, put the critical of stable austenite below than the environment temperature. As a consequence the investigated alloy is characterized by a PE behavior; it is able to recover the initial shape when load is null also over high values of deformation.

Specimen deformation and applied load were measured by means of a Linear Variable Differential Transformer (LVDT) and two load cells (10 kN each). The cycling testing specimens are shown in Figs 2.

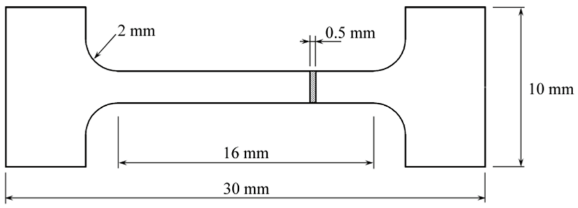


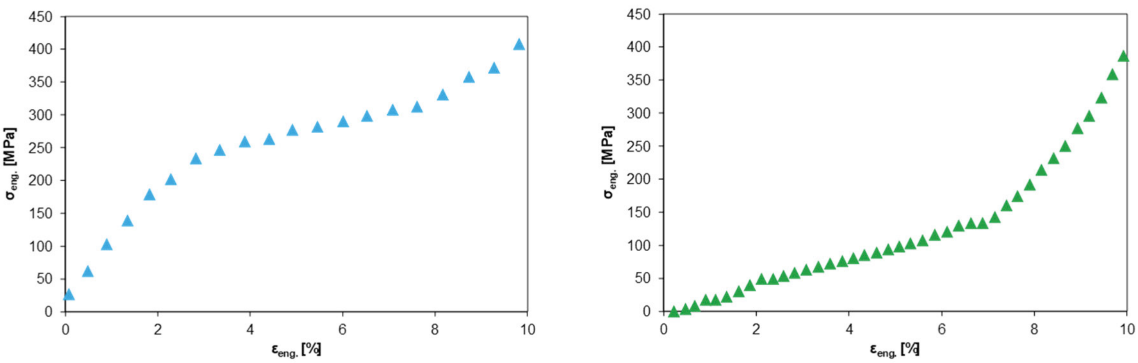
Fig. 2. Cycling specimen dimensions

Step by step isothermal tensile tests were carried out, at room temperature, at increasing values of the specimen elongation after 1, 10, 50 and 100 cycles. In particular, for each loading step the loading frame containing the specimen was removed from the testing machine, at fixed values of deformation, and analyzed by means of a Philips diffractometer in order to evaluate XRD spectra. XRD measurements were made with a Philips X-PERT diffractometer equipped with a vertical Bragg–Brentano powder goniometer.

A step–scan mode was used in the 2θ range from 30° to 90° with a step width of 0.02° and a counting time of 2 s per step. The employed radiation was monochromated CuKα (40 kV – 40 mA). The calculation of theoretical diffractograms and the generation of structure models were performed using the PowderCell software [20].

Furthermore, the gross engineering strain has been correlated to the effective engineering strain by a finite element simulation as reported in the following section.

Specimens cycled at 1 cycle and at 100 cycles have been used in a traditional tensile test up to failure in order to observe the differences of fracture micromechanisms due to the effect of cycles.



a) b)
Fig. 3. Stress-Strain behaviour of NiTi in the cycle 1: a) loading, b) unloading

3. Results

The tensile behaviour of the NiTi alloy is characterized by traditional three stages of the shape memory alloys: a first stage where the behaviour is the linear elastic range characterized by the young modulus of the austenite, a second stage where the slope sharply decreases and the mnicrostructure transforms fron the austenite to the martensite, and the third one where the behaviour bemane linear elastic with the young modulus of the martensite.

During the unload, the stages are almost the same, but beginning points, in terms of both stress and strain, change as a hysteresis phenomenon.

In Fig. 3 the differences of mechanical behaviour in case of loading and unloading is shown

The diffraction spectrum in unloading conditions, corresponding to the austenite microstructure is shown in Fig. 4, and the corresponding structure is a centred cubic with an atom of Ti in the center.

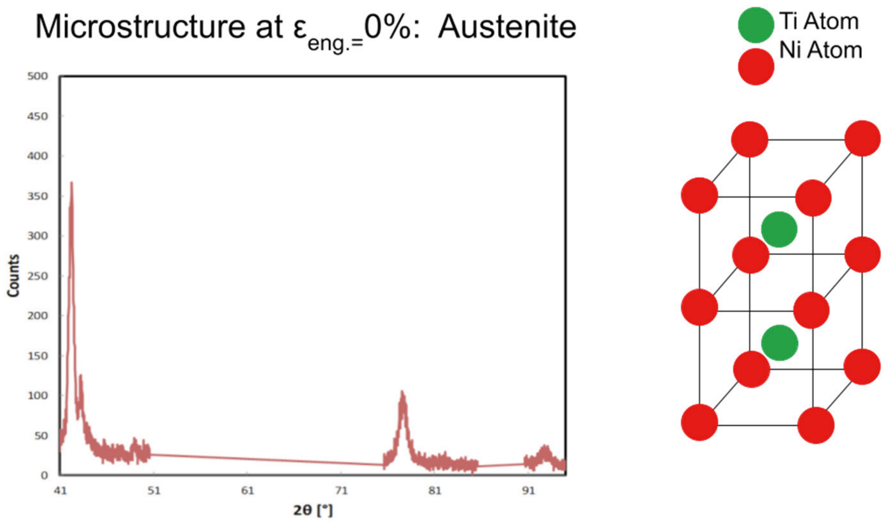


Fig. 4. Diffraction spectrum and microstructure of unloaded specimen

At high values of strains the microstructure changes in martensite. The spectrum of austenite is shown in Fig 5 where the lattice is a monoclinic one where the atoms of Ti and Ni are present on the vertex.

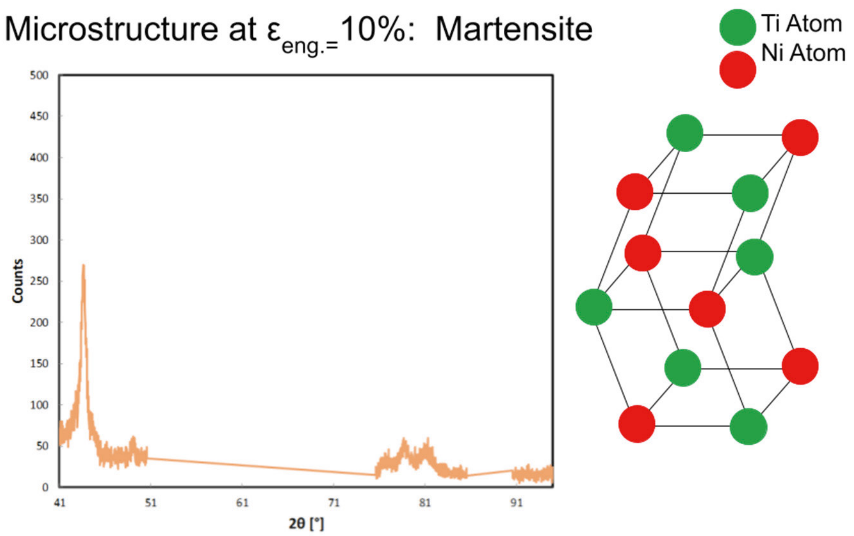


Fig. 5. Diffraction spectrum and microstructure of high loaded specimen

According to the model proposed by Di Cocco et al. 2018 and Berto et al. 2021, in order to calculate the mechanical behaviour of the Young modulus of the NiTi can be expressed by the relation (1)

$$E = \frac{A}{1+K_A\frac{\partial A}{\partial \varepsilon}}E_A + \frac{M}{1+K_M\frac{\partial A}{\partial \varepsilon}}E_M \tag{1}$$

where the amput of the austenite A and the martensite M can be calculate by the relations (2)

$$A = \frac{D\,e^{-C\varepsilon}}{1 + D\,e^{-C\varepsilon}}$$
$$M = 1 - \mathrm{A} = \frac{1}{1 + D\,e^{-C\varepsilon}} \tag{2}$$

Considering the values of parameters C and D (taken from Berto et al. 2021) the comparison between the cicle behaviour at cycle 100 is shown in Fig. 6.

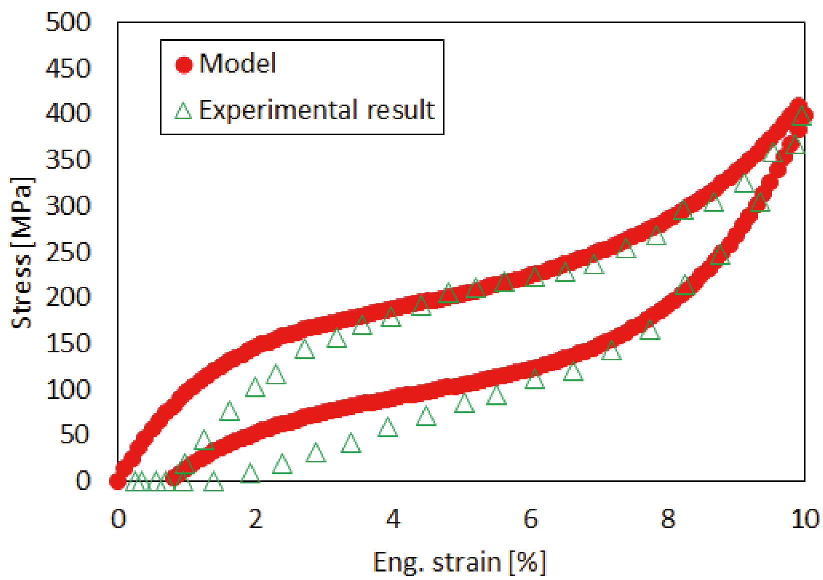
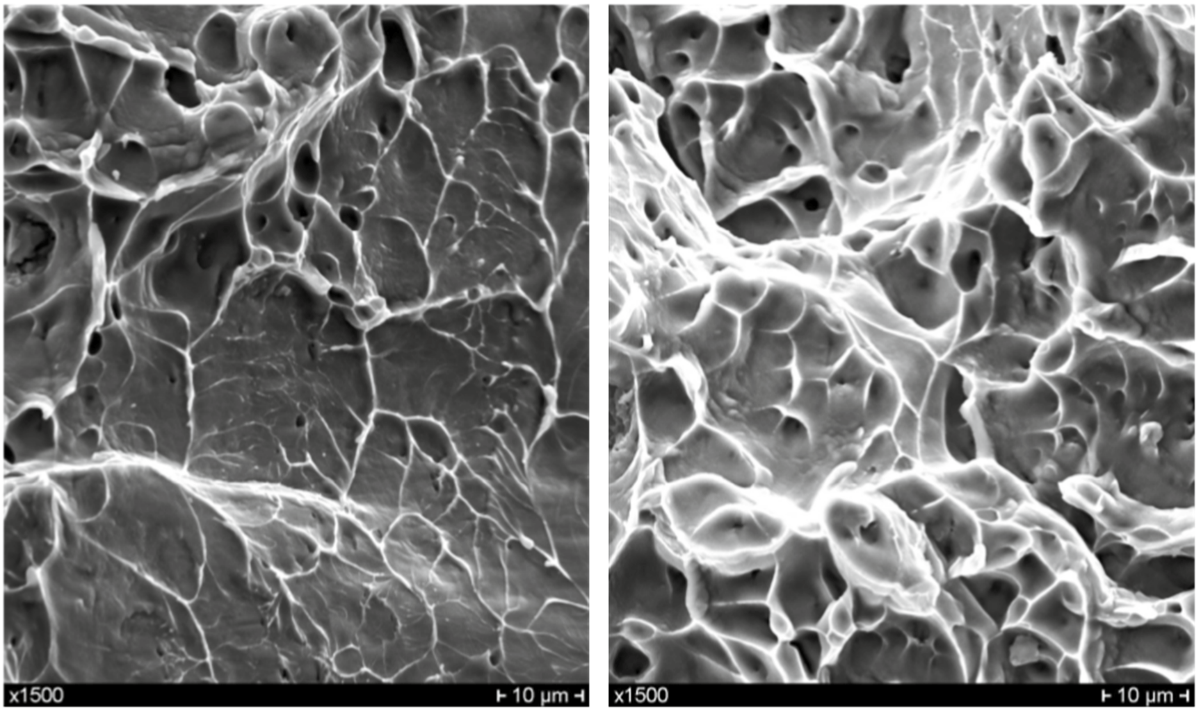


Fig. 6. Comparison of measured and calculate behaviour of NiTi at cycle 100

As shown the recovery of the initial shape isn't complete because there is some residual martensite which cannot change in the austenite. This is due to the cycle damage of the alloy.

Performing a traditional tensile test up to failure in specimens after 1 cycle and after 100 cycles the fracture surfaces are characterized by different fracture micromechanisms.

As shown in Fig. 7 the fracture surface of 1 cycle specimen is characterized by extensive zone characterized by a flat quasi-cleavage fracture micromechanisms, instead the 100 cycled fracture surface, where the main fracture micromechanisms is characterized by plastic deformation with presence of more dimples.



a) b)

Fig. 7. Tensile surface fracture observations: a) after 1 cycle, b) after 100 cycles

4. Conclusions

In this work an equiatomic NiTi shape memory alloy is used to study the cyclic evolution of the mechanical behaviour taking into account the real evolution of the austenite and the martensite. the results can be summarized as follows:

1) The transition of austenite to martensite and vice versa is characterized by a hysteresis phenomena
2) The model proposed by Berto et al. 2021 is able to predict the cyclic mechanical behaviour of Shape memory alloy which are characterized by a transition of austenite in martensite and vice versa without any other intermediate phase
3) The high cycled alloy is characterized by presence of residual martensite, probability due to the cyclic damaged alloy
4) The fracture surface of cycled specimens shown presence of more ductile fracture micromechanisms

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