NON-SYMMETRIC TENSION-COMPRESSION BEHAVIOUR OF NiTi ALLOY

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Abstract. Development of tensorial constitutive equations suitable to model the thermomechanical behaviour of shape memory alloys (SMA) would greatly help engineering design of sophisticated components. While a number of studies have focused on mechanical behaviour under tensile loading, only a few have been done to characterise properties under other stress states. The aim of our study is to report some new experimental results obtained on a equiatomic NiTi.

The experimental study was carried out using both uniaxial tension and compression tests which were performed with the same form for the specimens (sheet samples of gauge length 40mm and cross section 5.6mm×2.7mm) in order to avoid any geometrical effect. This choice allows to submit the material to the same prior thermomechanical treatment, i.e. a cold rolling leading to a thickness reduction of 18% followed by an annealing at 430°C for ½ hour. The temperature of the experiments were achieved using a silicon oil bath. A special device was designed in order to avoid buckling during compression. Preliminary tests were performed in order to study the effect of this device which was concluded as negligeable.

The results show that tension and compression behaviours are not symmetric, especially for superelastic behaviour. Moreover, the amplitude of the one-way memory effect and the slope of the linear variation of the transformation stress with the temperature are compared for these two stress states.

1. INTRODUCTION

In order to be able to design sophisticated components made of SMA, the development of tensorial constitutive equations suitable to model the thermomechanical behaviour of such materials is an essential step. The elaboration of constitutive laws generally requires experimental procedure, which consists in testing the material under various simple and homogeneous loadings. Different studies concerning SMAs' behaviour have already proved the importance of the loading path: for instance, Manach and Favier [1] have compared shear and tensile tests on a NiTi alloy, whereas Vacher and Lexcellent [3] have first shown the asymmetry between tension and compression with cylindrical samples made of Cu-based alloys. At the same time, Liu [4], Fillip and Mazanek [5], Lin and Wu [6] show that the whole material's thermomechanical history (heat treatment, colled-working...) affects drastically the material's behaviour. Therefore, mechanical tests have to be performed on the same material with identical initial treatment and under different loading paths, in order to get a correct behavioural characterisation. The present study exposes the results obtained with NiTi samples in tension and compression. The samples have been machined by spark-cutting in a cold-rolled and annealed sheet. The sheet form has been chosen for two main purposes. Firstly, a large part of NiTi industrial components are sheet-shaped (beams,shells...). Secondly, this shape is the only one allowing to perform homogeneous tests as tension, shear [1] and compression for materials submitted to identical various previous thermomechanical treatments.

The first part of this paper is devoted to the description of the used material: initial thermomechanical treatment, intrinsic datas, characterisation of the initial anisotropy. In the second part, we present the special device allowing tension and compression tests on sheet samples. Then, experimental results are exposed. They first describe qualitatively the behaviour difference between tension and compression, and then analyse more closely this phenomenon: recovery strains, evolutions of transformation stresses and transformation energies as functions of temperature are presented. The last part is devoted to the discussion on the eventual physical origins of such an asymmetry.

2. MATERIAL

2.1 Thermomechanical treatment

The experimental procedure was carried out using two types of mechanical tests, i.e. tension-compression tests and simple shear tests [1]. The studied material is an equiatomic NiTi ($Ni_{50}Ti_{50}$%at), supplied by Memometal Industry (France). The alloy has been supplied in the form of two sheets: one with an initial thickness of 3.2mm (for tension-compression tests) and the other with an initial thickness of 1.3mm (for the simple shear tests). The fabrication process for both sheets is the following one: vaccuum elaboration, wire drawing at 850°C to a diameter of 36mm, then hot-rolling at 850°C to a thickness of 3.2mm (respectively 1.3mm). In order to optimise the pseudoelastic response of the alloy [4], the following final treatment has been performed at the laboratory: homogenising at 900°C for 1h, cold-rolling with a 18 % thickness reduction and annealing at 430°C for ½ hour. After this treatment, the material showed a two stages transformation during cooling i.e. Austenite => R phase => Martensite, and one stage transformation on heating i.e. Martenstite => Austenite. A differential scanning calorimetry gave the following transformation temperatures: M_s =7°C, $M_f \approx$ -60°C, A_s =27°C, A_f = 56°C, R_s =53°C, R_f =35°C.

2.2 Anisotropy of the material induced by colled-rolling

In order to be able to analyse precisely the tension-compression results, it is very important firstly to characterise the anisotropy of the used material. A way to reveal an eventual initial anisotropy consists in performing simple shear tests with two 1.1mm samples: the first one cut in the rolled direction (RD), and the second one cut with 45° from the rolled direction (RD+45°). According to Manach's results [2], these two orientations would give the greatest difference for an anisotropic material. Several cyclic shear tests have been performed at different constant temperatures with a shear strain γ of ±12%. Figure 1 shows cyclic shear tests at T= 60°C. As observed by Manach [2], the cyclic shear behaviour is well symmetric. Furthermore, there is no significant difference between the two orientations so that the assumption of planar isotropy fits well with the used material. As the tension-compression tests have been performed on specimens of thickness 2.7mm, we have also checked that the two types of sheets (2.7 and 1.1mm) have the same mechanical behaviour, which have been achieved by comparing their tensile behaviour. For example figure 2 shows tensile test results realised at T=60°C (T>A_f) for the two thicknesses with a diagram [conventionnal stress *vs* logarithmic strain]: it is obvious that there is no significant influence of the thickness. Moreover, micro hardness tests have been performed on the 2.7mm NiTi sheet, showing that there is no significant variation of the Vickers number (300HV +/-1.5% in martensitic state) along the thickness and widthness. Therefore, anisotropy induced by colled-rolling can be neglected.

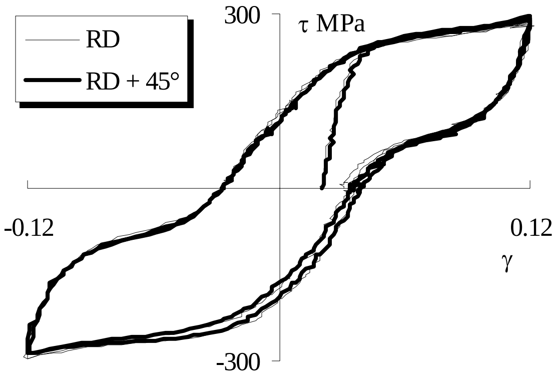

Figure 1: Cyclic shear tests at T= 60°C initial austenitic state

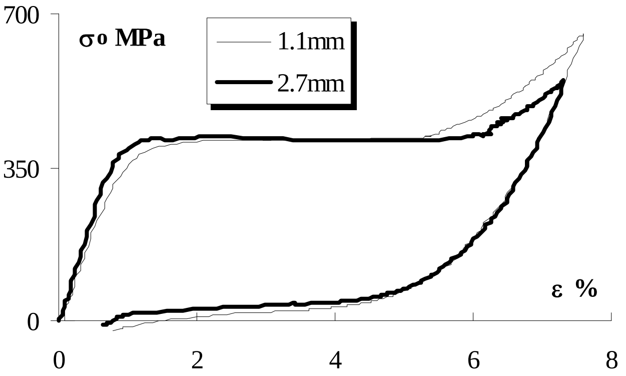

Figure 2: Tensile tests at T=60°, initial austenitic state

3. TENSION-COMPRESSION DEVICE

All the tension-compression tests were performed using an Adhamel-MTS mechanic testing machine with a maximum capacity of 2000 daN. The tensile device designed by Manach [2] is fixed on the machine. The temperature (-30°C to 100°C) is achieved by a silicon oil bath, controlled by an ultracryothermosat

Huber HS900 (±0.1°C). The elongation of the sample is measured by an extensometer directly connected to the sample, the gauge length being 12.5mm. For all tests, the crosshead displacement rate was 0.01mm/s. The originality of the device is that compression tests can be realised with sheet samples, because a special anti-buckling system is fixed all along the sample's gauge length. The oversimplified principle of the anti-buckling system is shown on figure 3a: this system does not disturb the expansion of the sample cross-section during a test, because of the Belleville washers. The specimens are bone shaped with a gauge length of 40mm, a total length of 100mm and a cross section of 2.7mm×5.6mm. A little groove (cross section of 1.2mm×0.8mm) has been machined on the samples to fix the anti-buckling system on the samples (figure 3b). All specimens have been machined by spark-cutting in order to avoid any hardening. Two types of samples were used. The first one (figure 3b) does not allow to use the extensometer and thus accurate measurement of the strain : it was only used to measure transformation stress levels. The second one (figure 3c) has been shaped so that local measurement of the strain with the extensometer is possible. The anti-buckling device has been perfected using mild steel samples, whose behaviour in tension-compression is known to be symmetric. The aim of the adjustment is to minimise the friction induced by the anti-buckling system by acting on the Belleville washers. Figure 3d shows a cyclic test in tension-compression with a mild steel specimen (conventionnal stress σ_o *vs* logarithmic strain ε): the curve is well symmetric. Moreover, figure 3e compares two tensile tests realised on two different NiTi samples (cut in the same sheet) at T= 60°C ($>A_f$). Whereas one sample is strained with the anti-buckling system, the other is strained without it: once again, if the adjustement of the Belleville washers is correct, friction induced by the anti-buckling device can be neglected.

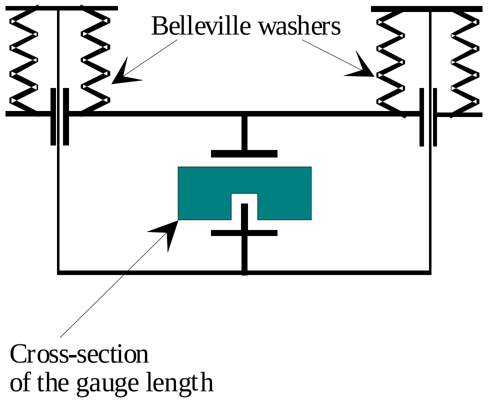

Figure 3a: Oversimplified principle of the anti-buckling system

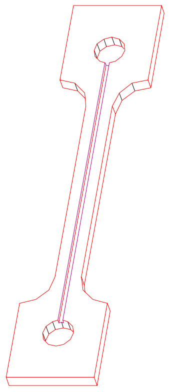

Figure 3b: Global measurement

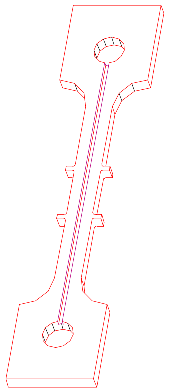

Figure 3c: Local measurement

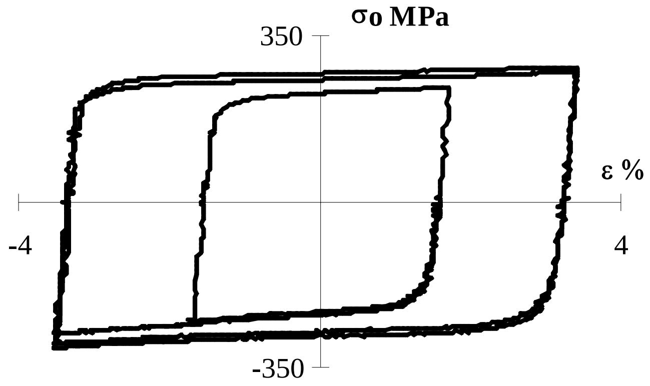

Figure 3d: Tension-compression test on mild steel

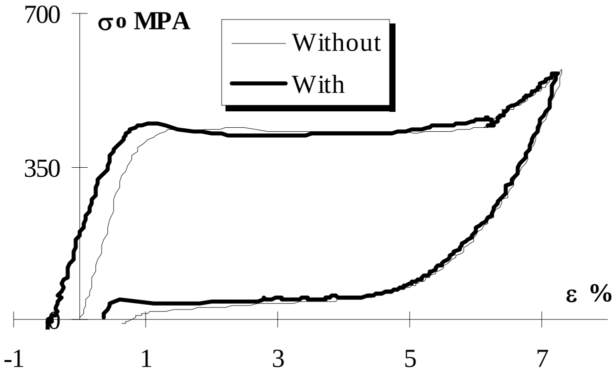

Figure 3e: Tensile test with and without the device

4. EXPERIMENTAL RESULTS

4.1 Qualitative tests

The aim of this part is to compare the tension and compression behaviours both during martensite reorientation and during martensitic transformation. Tension-compression tests with small strains (≈2%)

are then performed, at different temperatures. The tests show that with a deformation process induced by martensite reorientation, the material's behaviour is rather well symmetric in tension and compression (figure 4a). Conversely, there is a large difference between tension and compression, when the material is strained by martensitic transformation (figure 4b).

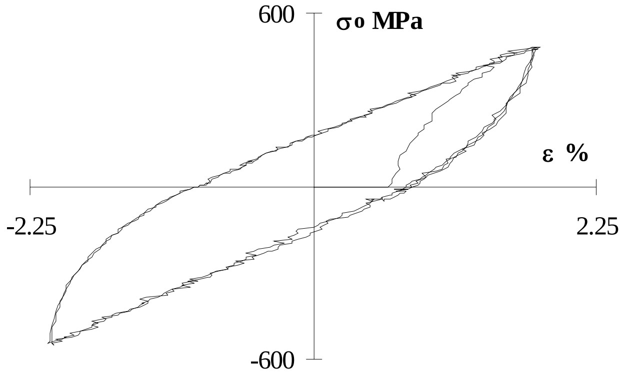

Figure 4a: Tension-compression test à T= 20°C, initial martensitic state

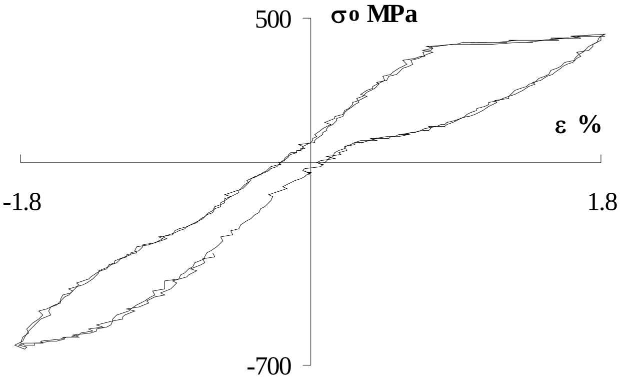

Figure 4b: Tension-compression test à T= 60°C, initial austenitic state

4.2 Analysis of the asymmetric behaviour in tension-compression

4.2.1 Influence of the loading path

The asymmetric behaviour during tension-compression tests has been observed during cyclic loadings so that it could be due to well known classical Bauschinger effect. To exclude this explanation, monotonic loadings have been performed in tension and in compression. Figure 5 shows monotonic tension and compression tests performed on two different samples at T= 60°C (T > A_f): the asymmetry is once again well observed.

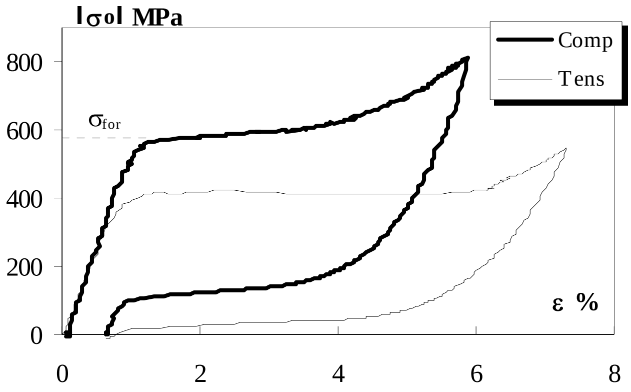

Figure 5: Tension and compression tests at T=60°C local measurement

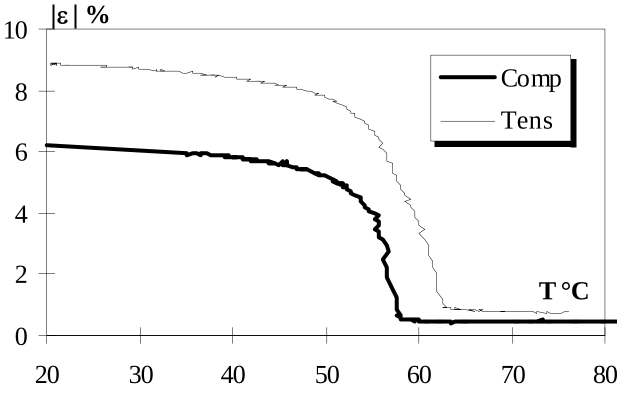

Figure 6: Evolution with T of recovery strains after simple tests at T= 21°C °

4.2.3 Recovery strains

In order to estimate the recovery strain, samples are first strained by martensitic transformation at T= 21°C (the testing temperature > M_s being reached by cooling) and then heated up to 75°C free of load. Figure 6 shows the evolution of the strains with the temperature during heating. Once again, the difference between tension and compression is obvious: the highest recovery strains are equal to 8.1% in tension and 5.75% in compression.

4.2.4 Variations of the transformation stresses with the temperature

The evolutions with the temperature of the forward transformation stresses (defined figure 5) both for tension and compression tests is plotted in figure 7: the material is strained by martensitic transformation during loading, since the test temperature is higher than M_s and reached by cooling the specimens. The asymmetry is also well observed, the transformation stress being about 35% higher in compression than in tension. The stresses' evolutions in the superelastic domain (50°C<T<70°C in compression and 50°C<T<90°C in tension) are nearly linear, the slopes being 8.5MPa/K in tension (in agreement with [4]) and 13MPa/K in compression respectively. In compression, the austenitic material reaches its yield point as early as 70°C, so that there isn't any well observed martensitic transformation above. The required energy to deform the material at the maximum transformation strain is estimated by the products [transformation stress × transformation strain]. The estimated transformation strains (figure 6) are 8.1% in tension and 5.75% in compression and are assumed to be temperature independent. Transformation energies (in J/g) are shown on figure 8 as functions of the testing temperature . The energy densities of transformation in tension and in compression increase linearly with the temperature (especially in the superelastic zone). Moreover, these energy densities are equal, the maximal relative difference being below 5%.

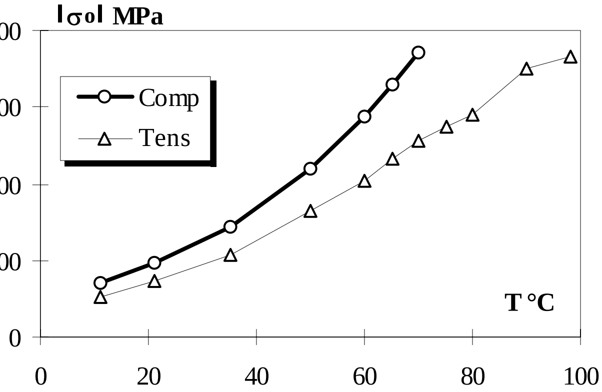

Figure 7: Evolution of the transformation stresses with T

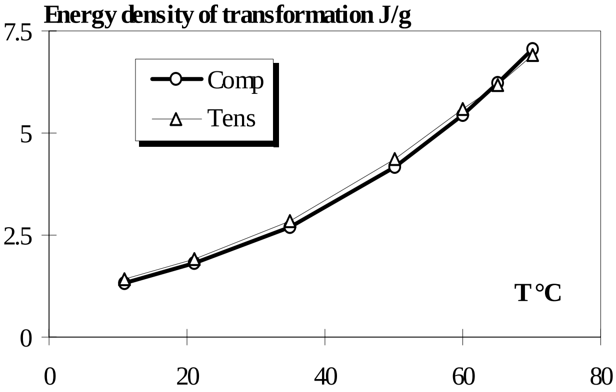

Figure 8: Evolution of the transformation energy with T

5. DISCUSSION

Several hypotheses have already been proposed to explain the Strenght Differential Effect (SDE) in SMA or other metallic materials that have neither anisotropy, nor Bauschinger effect. The aim of this part is to discuss the relevance of these explanations concerning the studied NiTi alloy.

5.1 Influence of hydrostatic pressure

This assumption originates from the study of the SDE observed in quenched and tempered steels [7]. In such a case, the yield locus is sensitive to hydrostatic pressure, so that the yield strength is higher in compression than in tension. This behaviour is observed when the deformation process leads to a volume expansion, so that the deformation is made easier in tension.

A similar hypothesis has been proposed by Vacher and Lexcellent [3] to explain the tension-compression asymmetry in SMA, the transformation stress being considered thus as sensitive to hydrostatic pressure. However, in NiTi alloys, as well as for Cu-Zn-Al alloys [9], martensitic transformation induces a weak and moreover negative volume change so that this effect should be weak and should lead to a transformation stress higher in tension than in compression.

5.2 Influence of the efficiency of the selected variants

Using a micro-mechanical approach on a non-textured Cu-Zn-Al alloy, Patoor *et.al.* [8] have recently observed a significant asymmetric behaviour in tension-compression: operating with a self-consistent scheme, the calculated transformation stresses and strains in tension have been found different than those calculated in compression. Both the low symmetry of the martensite phasis in Cu-Zn-Al alloys and the polycristalline structure inducing local stresses have been involved to explain the macroscopic tension-compression asymmetry. In order to check this explanation on NiTi alloys, similar micro-macro modellings have to be carried out, the habit planes and transformation directions being different than those for the Cu-Zn-Al alloys. To our knowledge, such studies have not been published. However, considering the resolved shear stress factor maps shown on figure 2 of [8], it is obvious that NiTi case is completely different from the Cu-Zn-Al one, so that the results obtained by Patoor *et.al.* can not be generalised without care for any SMA.

Although we are not able to precise the origin of the asymmetry, some useful informations can be drawn from results concerning the transformation energies shown on figure 8. These energies are proved to be independent of the sign of the bias stress (tension or compression) but only depend on the testing temperature. A similar noticing has already been done by Van Humbeeck and Delaey [10] concerning β-Cu-Zn-Al single cristals. The transforming energy was found as independent of the cristal orientation but as a function of the temperature: even if the stress-strain curves changed with the orientation, the required energy to transform the whole cristal from austenite to martensite was the same. From the results obtained on single cristals [10] and on polycristals during tension or compression tests (figure 8), it is concluded that the same martensite fraction has been induced in tension and in compression. Hence the tension-compression asymmetry observed in the stress-strain curves could be explained as following: the same martensite fraction is formed in tension and in compression but the orientation of martensite variants is more efficient in tension than in compression.

6. CONCLUSION

This experimental study has described the mechanical behaviour in tension and in compression of colled-rolled and annealed at 430°C NiTi alloy. In order to get rid of a maximum of inaccuracies, we paid a particular attention both to the thermomechanical history of the used material and to geometrical effects induced by samples' shape. For this last reason, a special anti-buckling system has been performed, allowing tension and compression on sheet samples.

Experimental results have shown that there is a significant asymmetry between tension and compression during deformation due to martensitic transformation. Transformation stresses are higher in compression than in tension, whereas it is the opposite concerning the recovery strains. From an energetic standpoint, the transformation energy densities in tension and in compression are equal. It has been proved that the origin of such an asymmetry is neither due to the antibuckling system, nor to the anisotropy of the material, nor to an eventual Bauschinger effect induced by mechanical cycling, nor to the material being sensitive to hydrostatic pressure.

From a physical standpoint, micro-structural origins of such a behaviour are to be analysed more closely. The macroscopic works to achieve the martensitic transformation of the polycristal are equal in tension and in compression. This demonstrates that the asymmetry of the transformation stresses and strains is due to different modes of deformation accomodation during stress induced martensitic transformation. To explain such a phenomenon on Cu-Zn-Al alloys, the roles of the low symmetry of the martensitic phase and local stresses induced by the polycristalline structure have been proved [8]. Similar studies have to be undertaken for NiTi alloys.

From a mechanical standpoint, it appears that a correct modelling of the NiTi behaviour has to take into account the role of the third invariant of the strain or stress tensors, as it has already been proposed by Patoor *et.al.* [8] on a Cu-Zn-Al alloy, using a Prager criterion to characterise phenomenologically the tension-compression asymmetry.

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