Influence d'un chargement thermomécanique cyclique sur les propriétés d'un alliage à mémoire de forme

M. Barati[a], L. Saint-Sulpice[b], S. Arbab Chirani[b], S. Callochc[c], M. Kadkhodaei[a]

a. Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
b. Institut de Recherche Dupuy de Lôme (IRDL FRE CNRS 3744) – École Nationale d'Ingénieurs de Brest (ENIB) – 945 Avenue Technopole, 29280 Plouzané, France
c. Institut de Recherche Dupuy de Lôme (IRDL FRE CNRS 3744) – ENSTA Bretagne – 2, rue François Verny, 29806 Brest cedex 9, France

Résumé :

Les alliages à mémoire de forme (AMF) sont utilisés dans de diverses industries telles que l'automobile, l'aérospatial, le génie civil et la bioingénierie. Dans la plupart de ces applications, l'alliage subit un chargement thermomécanique cyclique et est donc susceptible de rompre en fatigue. La fatigue des AMF est donc un problème clé qui doit être étudié pour encourager les applications techniques et l'utilisation plus efficace de leurs propriétés spécifiques d'effet mémoire de forme et de super-élasticité. Si un AMF est soumis à un chargement thermomécanique cyclique, une déformation inélastique apparaît et croit jusqu'à saturation après un certain nombre de cycles. Ce phénomène est à l'origine de la fatigue dans les AMF en entraînant une déformation résiduelle qui évolue avec les cycles. L'origine de cette déformation résiduelle au cours d'un chargement cyclique est l'un des plus grands problèmes pour la modélisation du comportement cyclique et en fatigue des AMF. Pour améliorer la fiabilité des systèmes à base d'AMF, il est donc important de prédire convenablement son évolution avec des modèles adaptés, et de proposer des critères de ruine adaptés. Ces critères doivent être basés sur des indicateurs de la déformation résiduelle cumulée. En particulier, deux interprétations micro-mécaniques sont abordées dans la littérature. L'une basée sur des contraintes résiduelles dues au développement de dislocations induites par le matériau au cours des cycles. L'autre, sur de la martensite résiduelle accumulée pendant l'éducation. La première interprétation considère que le changement progressif de la réponse de l'AMF sous chargement cyclique est due à la présence de contraintes résiduelles orientées qui apparaissent pendant l'arrangement des dislocations. La nucléation et la croissance de variantes de martensites préférentielles sont favorisées par ces contraintes résiduelles qui tendent à se relâcher pendant un changement de forme. De plus puisque la création de dislocations est strictement liée au développement de la plasticité, on peut en déduire que les effets de l'éducation sont connectés à de la déformation plastique résiduelle. La seconde interprétation est basée sur l'augmentation progressive de variantes de martensite orientée résiduelle qui apparaissent à cause de l'arrangement de dislocations. La présence de ces dislocations ne permet pas une transformation martensite-austénite complète au cours d'une décharge ou d'une chauffe. De plus, les petites plaquettes de martensite résiduelle croissent au cours des cycles suivants. Dans cette *étude, basée sur des observations et l'utilisation de mesures telles que la variation de résistance électrique, l'origine de la déformation résiduelle et l'augmentation progressive de la déformation résiduelle avec les cycles sont analysées. Une attention spéciale est portée à l'effet mémoire double sens obtenu après des chargements cycliques, et à sa relation avec le développement de la déformation résiduelle.*

Abstract :

Shape memory alloy (SMA) is widely used in various industries such as automotive, aerospace, civil and bioengineering. In most of the applications, the SMA is under thermomechanical cyclic loading and, therefore, susceptible to fatigue failure. Fatigue of shape memory alloys is a key issue that should be solved in order to promote their engineering applications and utilize their unique shape memory effect and superelasticity more sufficiently. If the SMA is subjected to thermomechanical cyclic loading, the permanent inelastic strain increases up to it reaches a stable value after a certain number of cycles. This procedure is at the origin of fatigue effect in SMA by introducing a residual strain which evolves with the cycles. The origin of the residual strain produce during a cyclic loading process is one of the most important problems facing for the modeling of the cyclic behavior and fatigue of SMAs. So, it is important to predict its evolution correctly with models to improve the reliability of SMA devices and to propose the well adapted fatigue criteria. These criteria should be based on the indicators of the cumulated residual strain. In particular, two micromechanical interpretations are discussed in literature, one based on residual stresses due to the development of dislocations induced in the material during the cycles, the other on residual permanent martensite accumulated during training. Referring to the first interpretation, the progressive change in the SMA response under cyclic loading is attributed to the oriented residual stresses occurring during the dislocations arrangement. The nucleation and growth of preferential martensite variants are favored by these residual stresses that tend to be relaxed by shape change. Moreover, since the generation of dislocations is strictly linked to the development of plasticity, it can be deduced that the training effects are connected with a residual plastic strain. The second interpretation is based on the progressive increment of the residual permanent oriented martensite variants that occur because of the dislocations arrangement. The presence of the dislocations does not allow the complete martensite–austenite transformation during the unloading and heating process. Moreover, the small residual martensite plates grow during subsequent cycles. In this study, based on the observations and using a measurement approach such as electric resistance variation, the origin of the residual strain is investigated and the progressive increase of residual strain with the increased cycle number is studied. A special attention is paid to two-way shape memory effect (TWSME) generated after considered cyclic loadings and its relation with the developed residual strain.

Mots clefs : alliage à mémoire de forme, comportement thermomécanique, effet mémoire double sens, déformation résiduelle

Introduction

Shape memory alloys (SMAs) have attracted great interests in developing smart structures and mechanisms. SMAs show very fascinating behaviors such as pseudoelasticity, one-way shape memory effect (OWSME), assisted two-way memory effect (ATWME) and two-way shape memory effect (TWSME).

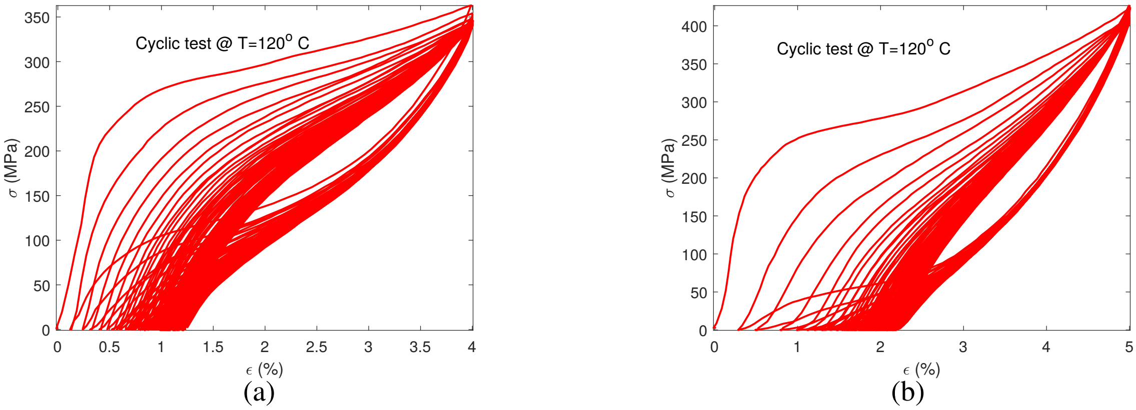
These behaviors are based on solid-solid diffusionless martensitic transformation. Different phases of the material, austenite, thermally-induced martensite and stress-induced martensite, are presented on the phase diagram. During each of these thermomechanical loadings, microstructure of an SMA varies, and the knowledge of such evolutions is important especially to develop reliable constitutive models. Another issue, whose investigation requires understanding of the microstructure, is residual strain. There are two different points of view about the origin of residual strain in shape memory alloys. The first group of researchers believes that accumulation of the residual strains during cyclic loadings is caused by a progressive increase of the residual permanent martensite [1–3]. They believe that the presence of dislocations leads to incomplete reverse transformations after each unloading cycle. This event results in accumulation of the residual martensite and produces permanent deformation. The second group believes that the accumulation of residual strain is due to irreversible slip of interface and dislocation creation in the cyclic deformations [4,5]. The second point of view is based on the classical theory of metal plasticity for the ratcheting phenomenon, which is observed during cyclic stress-controlled loading. Although these two different points of view have been considered for NiTi shape memory alloy [6, 7], there are not lots of results concerning an origin of residual strain for copper-based shape memory alloys. Transformation kinetics and microstructure of SMAs can be determined using different methods. X-ray and neutron diffraction techniques allow very detailed analyses on microstructure evolution during loading [7–14]. Optical micrography [15–18] and infrared thermography [19] are another methods, but they do not permit to quantitatively investigate the transformation kinetics. Transformation kinetics and microstructure can be investigated using macroscopic methods as well. In these methods, changes in material properties such as elastic modulus, magnetic properties and electric resistance are recorded simultaneously and continuously. Generally, based on these measurements which can be performed with no complicated experimental setup and after a well-adapted post-processing, the transformation kinetics can be determined [20]. Previous studies have shown that electric resistivity of a material is sensible to its microstructural state [20–23]. In the case of SMA, it has been shown to be a function of the thermally-induced martensite (M_T), stress-induced martensite (M_σ) and austenite (A) volume fractions. Hence, electric resistivity measurement provides a good tool to investigate phase changes in SMAs. In these regards, many efforts have been made to investigate variations of electric resistivity of SMAs under thermomechanical loadings [21–30]. In this paper, a three-phase proportioning method is developed and employed during different thermomechanical loadings to determine transformation kinetics in a CuAlBe SMA. A special experimental setup associated with a post-processing technic is used to determine the electric resistivity of the material as well as the volume fraction of each phase. SMA responses under different thermomechanical loadings may show a residual strain, which can evolve during complex cyclic loadings. In practice, development and evolution of residual strain can limit desirable functioning of SMA systems. The proposed phase proportioning method is used to investigate the origin of residual strain developed under different thermomechanical loadings for CuAlBe alloy. The TWSME generated after the development of residual strain is then studied.

Material and experimental set up

The utilized shape memory alloy in the present work is polycrystalline CuAlBe provided by Nimesis (France) with the composition of 87 % Cu, 11 % Al and 2 % Be. The material is available as wires with 0.8 mm diameter. Length of each sample is 230 mm, and a new sample is used for each experiment. All the thermomechanical tests are performed using a Zwick electromechanical testing machine (Zwick Z050) with a 500 N load cell. This machine is equipped with a thermal chamber (Zwick BW91250) with a controller unit (EUROTHERM 2216e). Temperature of the thermal chamber varies in the range of −80 °C to 250 °C. A 40 mm extensometer is used to accurately record the axial strain. Temperature is recorded by a K-type thermocouple placed on the studied samples. Diameter of the thermocouple is 0.08 mm. Isothermal mechanical tests are performed in quasi-static conditions with a low strain rate of $10^{-5}\,\mathrm{s}^{-1}$. The temperature rate of thermal cycles is $\pm 2\,°\mathrm{C}\cdot\mathrm{min}^{-1}$. The four-wire lead measurement approach is used to record the electric resistance variation of the sample under thermomechanical loadings.

Results and discussion

In this study, the residual strain during cyclic loadings and the generated TWSME behavior are investigated. A total number of 100 isothermal cycles at 120 °C are realized at strain controlled conditions. Two selective maximum strain values of 4 % and 5 % are imposed. The stress-strain results of these pseudoelastic cycles are demonstrated in figure 1.



(a) (b)

FIGURE 1 – Variations of the stress with strain during a cyclic tensile test at (a) 4 % strain amplitude and (b) 5 % strain amplitude.

A progressive reduction in the size of the hysteresis caused by the cyclic loading is observed. During the cyclic phase transformation, a progressive residual strain is accumulated with the number of cycles. However, as is seen in figure 2, the amount of residual strain for the maximum strain of 5 % is significantly greater than the one with 4 %.

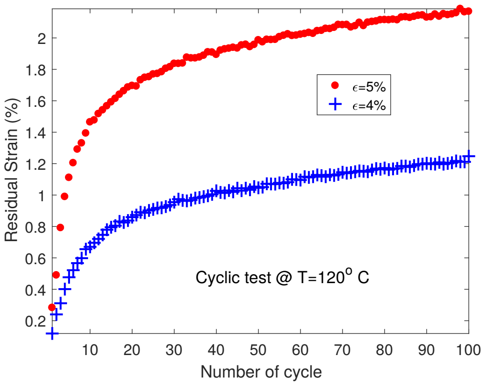
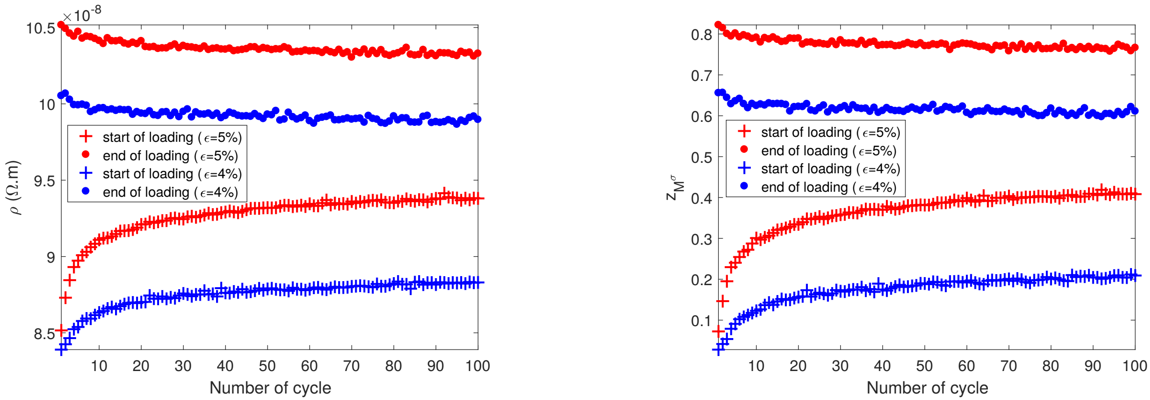


FIGURE 2 – Variations of the residual strain with number of cycles during cyclic tensile tests at 4 and 5 % strain amplitude.

In the case of cyclic test with the maximum strain of 5 %, the finally-obtained residual strain is about 2.17 % ; this is around 1.25 % for the case of 4 % maximum strain. Evolution of the material electric resistivity and the stress-induced martensite volume fraction at the start and the end of loading are depicted in figure 3 as a function of the number of cycles.



(a) (b)

FIGURE 3 – Variations of (a) the electric resistivity and (b) the stress-induced martensite volume fraction in the beginning of loading and unloading with the number of cycles.

The material electric resistivity and stress-induced martensite volume fraction at the beginning of each cycle increase with the number of cycles. After the mechanical cycles, as shown in figure 4, the applied thermal cycle is as follows : cooling from 120 °C (point A) to 20 °C (point B) ; then heating to 200 °C (point C), and cooling to 20 °C (point D) followed by re-heating to 120 °C (point E).

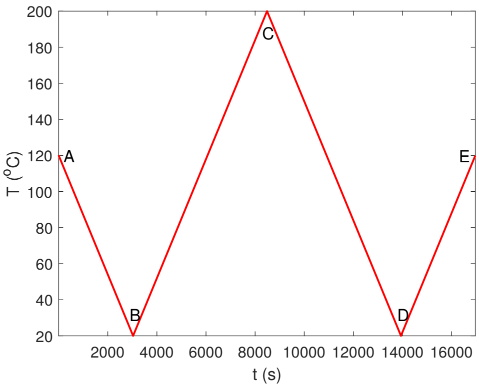
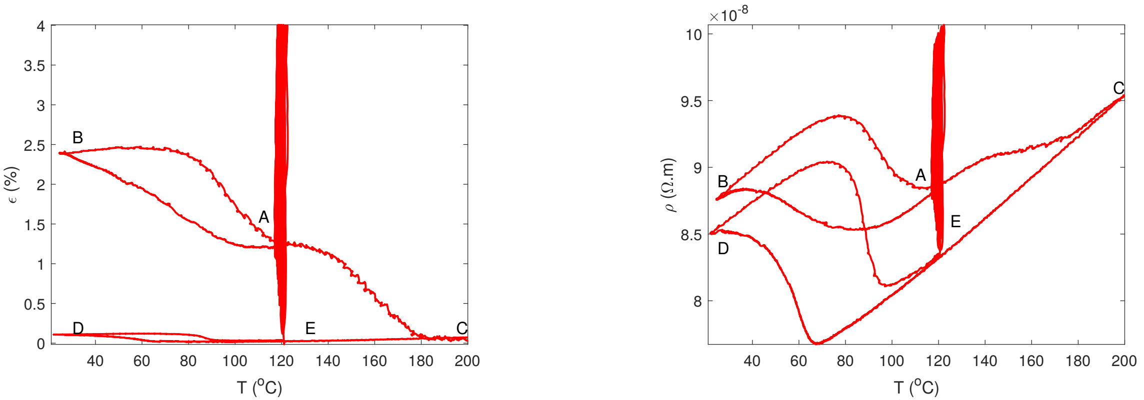


FIGURE 4 – Applied thermal cycle after cyclic pseudoelastic loading.

During the thermal cycle, between points A and B, TWSME is developed (figures 5(a) and 6(a)).

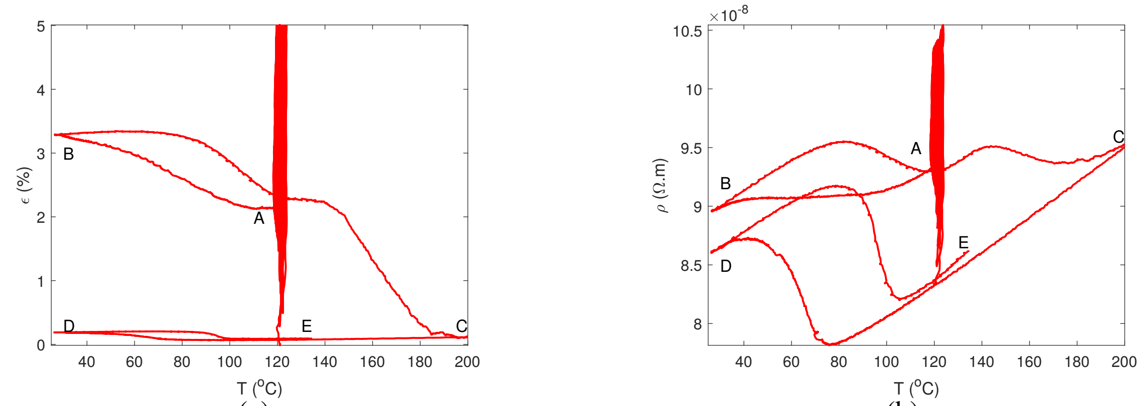
After heating up to 200 °C (point C), the residual strain (figures 5(a) and 6(a)) and the stress-induced martensite volume fraction (figure 7) are significantly reduced.

This heating permits to confirm that the origin of residual strain, for the considered CuAlBe SMA, is residual stress-induced martensite. Some defects are probably developed in the material which prevent the reverse transformation of stress-induced martensite to austenite. Indeed, if the origin of the residual strain was plasticity, the residual strain would not be recovered so much as shown in figures 5(a) and 6(a). Unlike the first cooling stage (from point A to B in figures 5(a) and 6(a)), during the last cooling stage (from point C to D in figures 5(a) and 6(a)), TWSME does not appear. It can be concluded that the



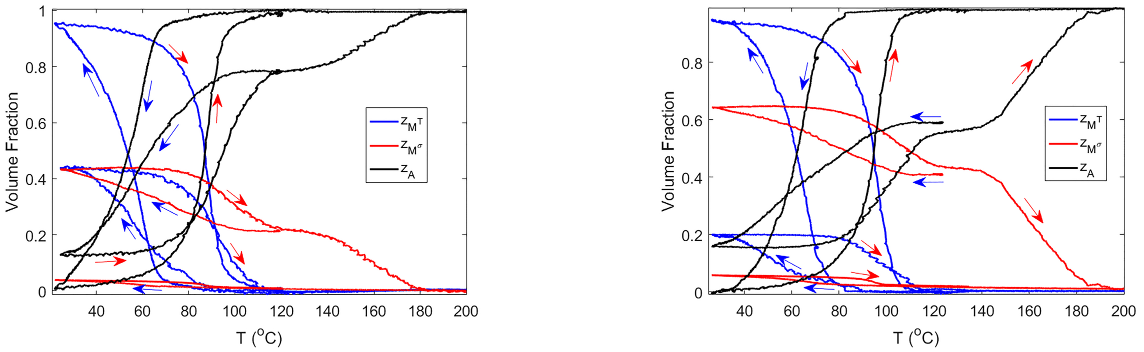
(a) (b)

FIGURE 5 – Variations of (a) the strain and (b) the electric resistivity with temperature for the samples under cyclic pseudoelastic loading with a maximum strain of 4 %.



(a) (b)

FIGURE 6 – Variations of (a) the strain and (b) the electric resistivity, with temperature for the samples under cyclic pseudoelastic loading with a maximum strain of 5 %.



(a) (b)

FIGURE 7 – Evolution of different volume fractions after cyclic pseudoelastic loading for the test with maximum strain of (a) 4 % and (b) 5 %.

residual stress-induced martensite is the origin of the TWSME.

Finally, the proposed phase proportioning method confirms that the origin of the residual strain is the residual stress-induced martensite. Its existence permits to obtain TWSME. This is confirmed by heating up to 200°C (figure 7). Volume fraction of stress-induced martensite decreases seriously. And the last cooling does not relieve TWSME as well as the first cooling.

Conclusion

In this paper the microstructure evolution of a CuAlBe SMA under thermomechanical loadings are studied. This was possible using in-situ electric resistance measurements with a well-adapted post processing method. By this way the volume fractions of the three phases of the SMA are determined. The origin of residual strain observed during the considered thermomechanical loadings is discussed. It is concluded that the origin of residual strain, for considered CuAlBe SMA, is residual stress-induced martensite and its existence permits to obtain TWSME. Pseudoelastic cyclic loading and generated TWSME are also investigated. It is shown that, if residual stress-induced martensite is removed, TWSME disappears. These comprehensive experimental results, with enriched information on transformation kinetics, permit to identify and to validate numerical models of SMAs behaviors.

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