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► **To cite this version:**

Mahmoud Barati, Luc Saint-Sulpice, Shabnam Arbab-Chirani, Sylvain Calloch, Shabnam Arbab Chirani. Influence d'un chargement thermomécanique cyclique sur les propriétés d'un alliage à mémoire de forme. CFM 2017 - 23ème Congrès Français de Mécanique, Aug 2017, Lille, France. hal-03465575

HAL Id: hal-03465575

<https://hal.science/hal-03465575>

Submitted on 3 Dec 2021

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

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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 croît 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} s^{-1} . The temperature rate of thermal cycles is $\pm 2^{\circ}\text{C}\cdot\text{min}^{-1}$. 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.

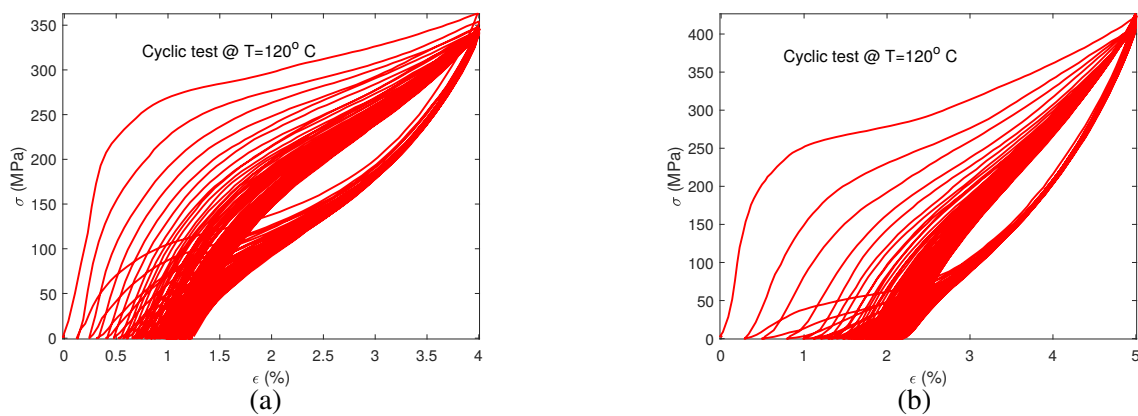


FIGURE 1 – Variations of the stress with strain during a cyclic tensile test at (a) 4 % strain amplitude and (b) 5 % strain amplitude.

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 %.

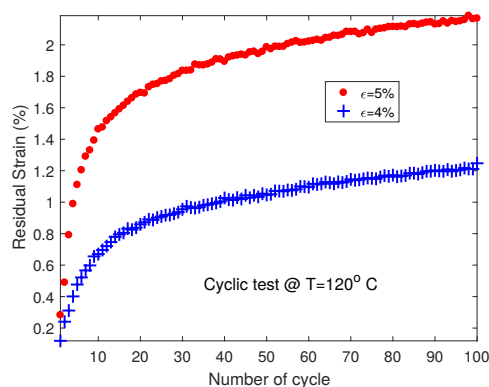


FIGURE 2 – Variations of the residual strain with number of cycles during cyclic tensile tests at 4 and 5 % strain amplitude.

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.

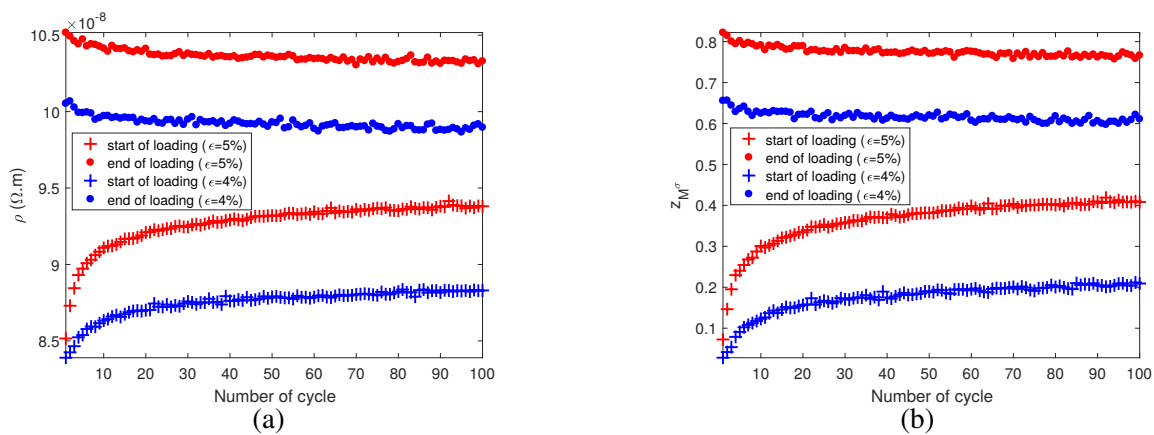


FIGURE 3 – Variations of (a) the electric resistivity and (b) the stress-induced martensite volume fraction in the beginning of loading and unloading with the number of cycles.

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).

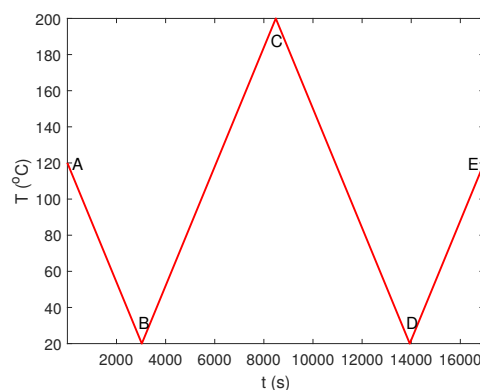


FIGURE 4 – Applied thermal cycle after cyclic pseudoelastic loading.

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

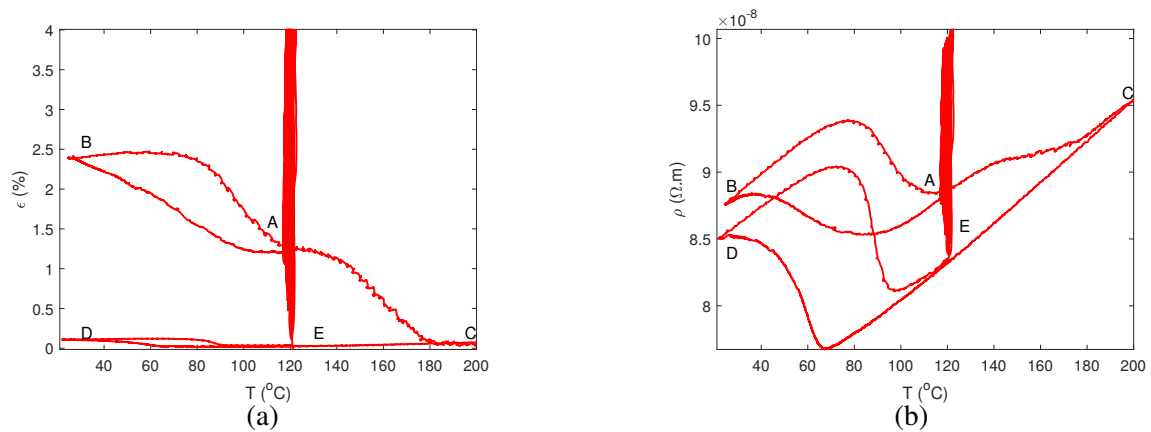


FIGURE 5 – Variations of (a) the strain and (b) the electric resistivity with temperature for the samples under cyclic pseudoelastic loading with a maximum strain of 4 %.

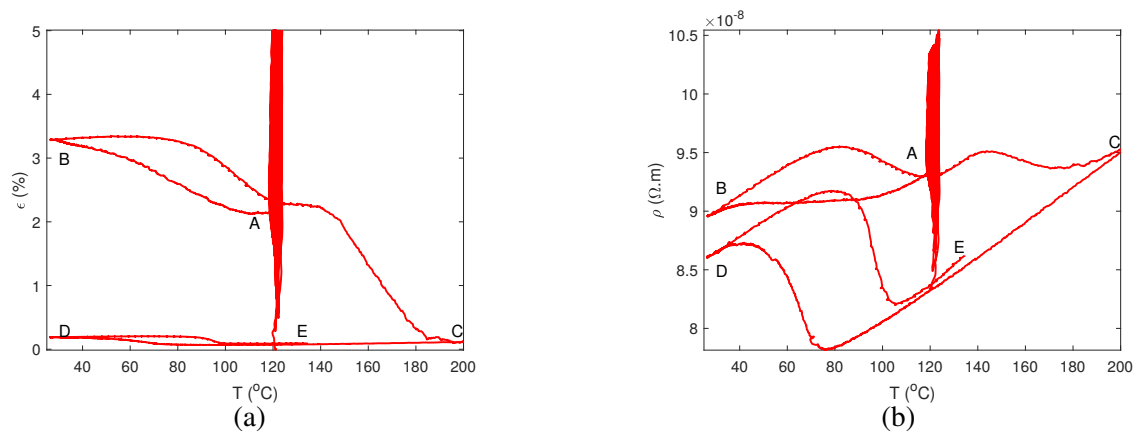


FIGURE 6 – Variations of (a) the strain and (b) the electric resistivity, with temperature for the samples under cyclic pseudoelastic loading with a maximum strain of 5 %.

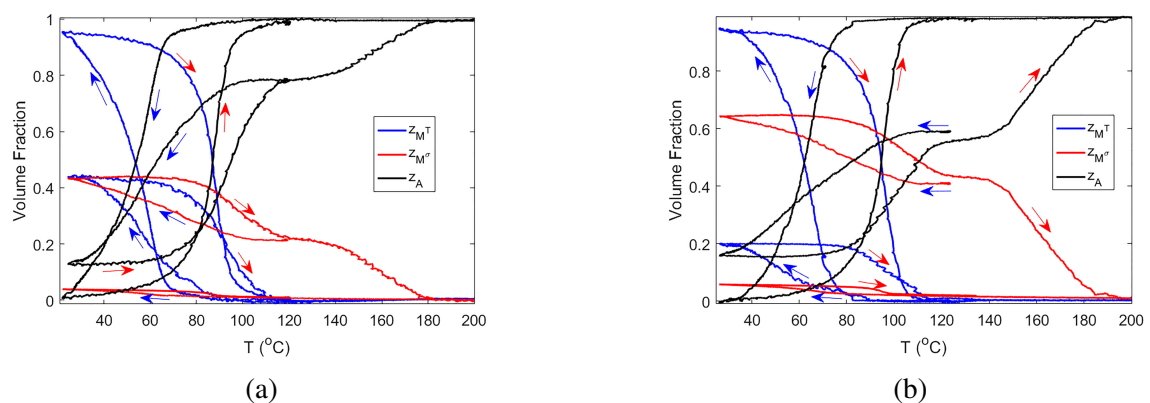


FIGURE 7 – Evolution of different volume fractions after cyclic pseudoelastic loading for the test with maximum strain of (a) 4 % and (b) 5 %.

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.

Références

- [1] LUC SAINT-SULPICE, Shabnam ARBAB CHIRANI et Sylvain CALLOCH : Super-elastic behavior of shape memory alloys under proportional cyclic loadings. *Materials Science and Engineering : A*, 481–482:174–177, mai 2008.
- [2] LUC SAINT-SULPICE, Shabnam ARBAB CHIRANI et Sylvain CALLOCH : A 3d super-elastic model for shape memory alloys taking into account progressive strain under cyclic loadings. *Mechanics of Materials*, 41(1):12–26, janvier 2009.
- [3] LUC SAINT-SULPICE, Shabnam ARBAB CHIRANI et Sylvain CALLOCH : Thermomechanical cyclic behavior modeling of Cu-Al-Be SMA materials and structures. *International Journal of Solids and Structures*, 49(9):1088–1102, mai 2012.
- [4] Zhonghe Bo et Dimitris C. LAGODAS : Thermomechanical modeling of polycrystalline SMAs under cyclic loading, Part III : evolution of plastic strains and two-way shape memory effect. *International Journal of Engineering Science*, 37(9):1175–1203, juillet 1999.
- [5] Dirk HELM et Peter HAUPT : Shape memory behaviour : modelling within continuum thermomechanics. *International Journal of Solids and Structures*, 40(4):827–849, février 2003.
- [6] F. AURICCHIO, S. MARFIA et E. SACCO : Modelling of SMA materials : Training and two way memory effects. *Computers & Structures*, 81(24–25):2301–2317, septembre 2003.
- [7] P. SEDMÁK, P. ŠITTNER, J. PILCH et C. CURFS : Instability of cyclic superelastic deformation of NiTi investigated by synchrotron X-ray diffraction. *Acta Materialia*, 94:257–270, août 2015.
- [8] J. PONS, F. C. LOVEY et E. CESARI : Electron microscopy study of dislocations associated with thermal cycling in a Cu-Zn-Al shape memory alloy. *Acta Metallurgica et Materialia*, 38(12):2733–2740, décembre 1990.
- [9] Xiaoping JIANG, Moritaka HIDA, Yoshito TAKEMOTO, Akira SAKAKIBARA, Hidehiro YASUDA et Hiroto MORI : In situ observation of stress-induced martensitic transformation and plastic deformation in TiNi alloy. *Materials Science and Engineering : A*, 238(2):303–308, novembre 1997.
- [10] H SITEPU, W. W SCHMAHL, J. K ALLAFI, G EGGELER, A DLOUHY, D. M TOEBBENS et M TOVAR : Neutron diffraction phase analysis during thermal cycling of a Ni-rich NiTi shape memory alloy using the Rietveld method. *Scripta Materialia*, 46(7):543–548, avril 2002.

- [11] Ganesh K. KANNARPADY, Abhijit BHATTACHARYYA, Mike WOLVERTON, Donald W. BROWN, Sven C. VOGEL et Sergei PULNEV : Phase quantification during pseudoelastic cycling of Cu-13.1 Al-4.0ni (wt. %) single-crystal shape memory alloys using neutron diffraction. *Acta Materialia*, 56(17):4724–4738, octobre 2008.
- [12] N. G. JONES, S. L. RAGHUNATHAN et D. DYE : In-Situ Synchrotron Characterization of Transformation Sequences in TiNi-Based Shape Memory Alloys during Thermal Cycling. *Metallurgical and Materials Transactions A*, 41(4):912–921, avril 2010.
- [13] R. DELVILLE, B. MALARD, J. PILCH, Petr ŠITTNER et D. SCHRYVERS : Transmission electron microscopy investigation of dislocation slip during superelastic cycling of Ni–Ti wires. *International Journal of Plasticity*, 27(2):282–297, février 2011.
- [14] Benoit MALARD, Petr SITTNER, Sophie BERVEILLER et Etienne PATOOR : Advances in martensitic transformations in Cu-based shape memory alloys achieved by in situ neutron and synchrotron X-ray diffraction methods. *Comptes Rendus Physique*, 13(3):280–292, avril 2012.
- [15] S. MIYAZAKI, T. IMAI, Y. IGO et K. OTSUKA : Effect of cyclic deformation on the pseudoelasticity characteristics of Ti-Ni alloys. *Metallurgical Transactions A*, 17(1):115–120, janvier 1986.
- [16] S. MIYAZAKI, K. OTSUKA et C. M. WAYMAN : The shape memory mechanism associated with the martensitic transformation in Ti-Ni alloys—I. Self-accommodation. *Acta Metallurgica*, 37(7):1873–1884, juillet 1989.
- [17] S. MIYAZAKI, K. OTSUKA et C. M. WAYMAN : The shape memory mechanism associated with the martensitic transformation in Ti-Ni alloys—II. Variant coalescence and shape recovery. *Acta Metallurgica*, 37(7):1885–1890, juillet 1989.
- [18] L. Catherine BRINSON, Ina SCHMIDT et Rolf LAMMERING : Stress-induced transformation behavior of a polycrystalline NiTi shape memory alloy : micro and macromechanical investigations via in situ optical microscopy. *Journal of the Mechanics and Physics of Solids*, 52(7):1549–1571, juillet 2004.
- [19] D. DELPUEYO, X. BALANDRAUD et M. GRÉDIAC : Applying infrared thermography to analyse martensitic microstructures in a Cu-Al-Be shape-memory alloy subjected to a cyclic loading. *Materials Science and Engineering : A*, 528(28):8249–8258, octobre 2011.
- [20] LUC SAINT-SULPICE, Mohamed LAKRIT, Shabnam ARBAB CHIRANI et Sylvain CALLOCH : Variation in electric resistivity in metastable alloys during thermomechanical loading : Effects of temperature, elasticity, plasticity and phase transformation. *Mechanics of Materials*, 71:1–9, avril 2014.
- [21] C. H. GONZALEZ, M. MORIN et G. GUÉNIN : Behaviour of electrical resistivity in single crystals of Cu-Zn-Al and Cu-Al-Be under stress. *Le Journal de Physique IV*, 11(PR8):Pr8–167–Pr8–172, novembre 2001.
- [22] V. NOVÁK, Petr ŠITTNER, G. N. DAYANANDA, F. M. BRAZ-FERNANDES et K. K. MAHESH : Electric resistance variation of NiTi shape memory alloy wires in thermomechanical tests : Experiments and simulation. *Materials Science and Engineering : A*, 481–482:127–133, mai 2008.
- [23] Pierre-Antoine GÉDOUIN, Shabnam ARBAB CHIRANI et Sylvain CALLOCH : Phase proportioning in CuAlBe shape memory alloys during thermomechanical loadings using electric resistance variation. *International Journal of Plasticity*, 26(2):258–272, février 2010.
- [24] C. J DE ARAUJO, M MORIN et G GUÉNIN : Electro-thermomechanical behaviour of a Ti-45.0 Ni-5.0 Cu (at.%) alloy during shape memory cycling. *Materials Science and Engineering : A*, 273–275:305–309, décembre 1999.

- [25] J UCHIL, K. K MAHESH et K. Ganesh KUMARA : Electrical resistivity and strain recovery studies on the effect of thermal cycling under constant stress on R-phase in NiTi shape memory alloy. *Physica B : Condensed Matter*, 324(1–4):419–428, novembre 2002.
- [26] E LÓPEZ CUÉLLAR, G GUÉNIN et M MORIN : Study of the stress-assisted two-way memory effect of a Ti–Ni–Cu alloy using resistivity and thermoelectric power techniques. *Materials Science and Engineering : A*, 358(1–2):350–355, octobre 2003.
- [27] Cezar Henrique GONZALEZ, Ney Freitas de QUADROS, Carlos José de ARAÚJO, Michel MORIN et Gerard GUÉNIN : Coupled stress-strain and electrical resistivity measurements on copper based shape memory single crystals. *Materials Research*, 7(2):305–311, juin 2004.
- [28] N. MA, G. SONG et H.-J. LEE : Position control of shape memory alloy actuators with internal electrical resistance feedback using neural networks. *Smart Materials and Structures*, 13(4):777, 2004.
- [29] S. K. WU, H. C. LIN et T. Y. LIN : Electrical resistivity of Ti–Ni binary and Ti–Ni–X (X = Fe, Cu) ternary shape memory alloys. *Materials Science and Engineering : A*, 438–440:536–539, novembre 2006.
- [30] V. ANTONUCCI, G. FAIELLA, M. GIORDANO, F. MENNELLA et L. NICOLAIS : Electrical resistivity study and characterization during NiTi phase transformations. *Thermochimica Acta*, 462(1–2):64–69, octobre 2007.