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Investigation of martensitic microstructures in a monocrystalline Cu–Al–Be shape memory alloy with the grid method and infrared thermography

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ABSTRACT

The objective of the study is to analyze the martensitic microstructure evolution in a shape-memory alloy during a stress-induced transformation. Two full-field measurement techniques are used for this purpose: the grid method to obtain strain maps and infrared thermography to measure temperature variation maps at the same time. The specimen is a monocrystalline Cu–Al–Be alloy which is austenitic at ambient temperature. Austenite progressively transforms into martensite during the mechanical loading and the impact of this transformation in terms of strain and temperature is analyzed in this paper. The spatial resolution of the strain maps obtained enables us to distinguish some typical martensitic microstructures such as martensite needles, habit planes and X-shaped microstructures, so the evolution of these microstructures during the test is presented and discussed with strain maps obtained at some points regularly spaced on the stress–strain curve. Infrared thermography provides some additional information to analyze the transformation phenomena. Maps of latent heat are calculated from temperature maps thanks to a specific post-processing procedure. Interestingly, the microstructure evolution during the loading phase is found to be different of the evolution during the unloading phase although the specimen precisely returns to zero strains at the end of the cycle. In the last part of the paper, the values of the measured in-plane strain components are used to identify the martensite variants that likely appear in the specimen during the loading phase of the test. This identification is based on some crystallographic compatibility calculations.

1. Introduction

Shape-memory alloys feature peculiar properties such as superelasticity or the ability to return to their initial shape after deformation and heating above a certain characteristic temperature which depends on the material. These properties are mainly due to a reversible austenite/martensite phase transformation that occurs within the material when it is subjected to a mechanical load or to a change of temperature. Martensite is generally present in typical microstructures such as martensite twins, habit planes, wedges, needles, crossing bands or X-shaped microstructures (Bhattacharya, 2003). Many studies aimed at studying these microstructures for a better understanding of superelasticity or shape memory phenomenon are available in the literature. Classic means such as microscopes are generally used to observe them, but the recent development of full-field measurement techniques has made it possible to observe phase transformations in detail. An interest of these techniques is to provide quantitative thermo-mechanical information within the phases themselves, either in terms of temperature, heat source, displacement or strain distributions. Heat source and

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strain fields are generally derived from temperature variation and displacement fields, respectively, using a suitable image processing technique. The spatial distribution of the phases on the surface of the specimens can also be observed by analyzing the contrast in the strain or in the heat source maps. This is due to the fact that the strain level generally changes from one phase to each other and that phase transformation is a phenomenon that is accompanied by latent heat. For instance, Zhang et al. used moiré interferometry to analyze the displacement field due to martensitic transformation in a single crystal of Cu—Al—Ni (Zhang et al., 1997). The technique used in more recent studies to measure displacement fields is digital image correlation (DIC), whose main feature is to track with a CCD camera speckles randomly deposited on the surface under investigation and to deduce the displacement field by image processing (Sutton et al., 2009). The sensitivity is worse than that of moiré interferometry, but it is much more user-friendly because this is a non-interferometric technique. In Efstathiou et al. (2008) for instance, the authors employed DIC to study intermartensitic transformations in a Ni—Fe—Ga single crystal. The same technique has been used to compare experimental strain fields with their numerical counterparts that occurred in a Cu–Al–Be SMA multicrystal (Merzouki et al., 2010), to study the development of martensite in Nitinol (Daly et al., 2007, 2009) or to investigate local transformations in precipitated Ni—Ti single crystals (Efstathiou and Sehitoglu, 2008). In Sanchez-Arevalo et al. (2009), the metrological performances of DIC and digital speckle pattern correlation are compared to measure displacement fields in a Cu–Al–Be SMA. Phase transformation is also accompanied with latent heat that can be deduced from temperature variation fields measured with infrared cameras. Such cameras can be used alone (Balandraud et al., 2001; Delpueyo et al., 2011) or in combination with displacement/strain measurement techniques (Favier et al., 2007) to study phase transformations in SMAs.

In this context, the aim of this work is twofold. The detailed evolution of the phase transition in a Cu–Al–Be monocrystalline specimen subjected to a quasi-static tensile test is first presented and discussed. Two complementary full-field measurement techniques were used: the grid method and infrared thermography. These techniques provide strain and heat source fields after a suitable processing of images taken on the two opposite faces of the specimen. A CCD camera and an infrared camera were used to take these images. The second objective is to show that the strain maps obtained during the loading phase of the test can be employed to identify martensite variants from considerations concerning compatibility calculations.

Both the grid method and infrared thermography are briefly presented in the first part of the paper. The martensitic microstructures that can be detected in the strain and heat source maps obtained at different stages of the stress–strain curve are then presented and discussed. Some strain maps obtained during the loading phase are finally processed to identify the martensite variants that likely appeared during the loading phase of the test.

2. Specimen preparation and experimental setup

2.1. Specimen

2.1.1. Composition and dimensions

The specimen was made of a monocrystalline Cu $Al_{11.4}$ $Be_{0.5}$ (wt.%) SMA. It was prepared by vertical Bridgman method by Nimesis Technology (Metz, France). The ingot was cut in slices by electro-erosion to obtain specimens exhibiting the desired dimensions: $0.94 \times 17.78 \times 72\ mm^3$ along directions x, y and z, respectively. Aluminium tabs were bonded at the ends of the specimen to avoid any damage that occurred when tightening the grips of the testing machine. The gauge length along the z-direction was equal to 53 mm ± 1 mm.

2.1.2. Material properties

Some material parameters must be known for the post-processing and the analysis of the results presented below. The specimen was austenitic at ambient temperature 22 °C since its martensite start temperature was equal to −2 °C. The orientation of the cubic austenitic crystal was measured by X-ray diffraction. The (1 0 1) plane was found to be nearly parallel to the (y,z) plane, which corresponds to the front of the specimen (the angle between the normals of these planes was equal to 6.9 deg). The z- (or longitudinal) direction of the specimen was nearly parallel to the [0 1 0] crystal direction (the angle is equal to 5.7 deg in this case). The rotation matrix denoted $\mathbf{R}_{\mathbf{c}\to\mathbf{s}}$ from the cubic axes ([1 0 0], [0 1 0], [0 0 1]) to the specimen axes (x,y,z) is as follows

$$\mathbf{R}_{\mathbf{c}\to\mathbf{s}} = \begin{pmatrix} -0.773 & -0.664 & 0.000 \\ -0.066 & 0.079 & 0.995 \\ -0.631 & 0.769 & -0.103 \end{pmatrix} \tag{2.1}$$

The alloy under study exhibits a M18R martensite (see Balo et al., 2001; Hsu et al., 2009) dealing with alloys featuring quite similar compositions). The stretch parameters related to the phase transformation can be calculated from the lattice parameters of the two phases. Some sets of lattice parameters in Cu–Al–Be SMAs are available in the literature (Moreau et al., 1995; Balandraud and Zanzotto, 2007; Hsu et al., 2009). Since these data do not exactly correspond to the composition of the alloy under study, it was decided to determine the stretch parameters directly from the strain measurements performed in the present study (see Section 4.6).

Finally, it was also necessary to know the thermal diffusivity tensor of the austenite and the martensite SMA crystals to perform the thermal analysis of the temperature maps described below (see Section 2.3.3). To the best knowledge of the authors however, the anisotropic thermal diffusivity tensor of martensite is not available in the literature. Consequently and for the sake of simplicity, the thermal diffusivity tensors of both the austenite and the martensite were assumed to be isotropic and equal. The thermal diffusivity D was measured using the following procedure. The specimen was first heated and then naturally cooled by ambient air. The temperature measured during the cooling phase was processed to deduce D.