

Chapter 2

Measurement of Mechanical Dissipation in SMAs by Infrared Thermography

Didier Delpueyo, Xavier Balandraud, Michel Grédiac, Sergiu Stanciu, and Nicanor Cimpoesu

Abstract The reversibility of the phase transformation in shape-memory alloys (SMAs) directly governs the mechanical response of these materials. Infrared thermography is used in this study to measure the mechanical dissipation produced by copper-based SMAs under cyclic loading at ambient temperature. Several specimens with different chemical compositions are tested. Mechanical dissipation which is produced by the material is deduced from the temperature change using a 0D version of the heat equation. Results obtained show that the chemical composition as well as the nature of the phase involved (martensite or austenite) influence the mechanical dissipation produced by the specimens during cyclic mechanical loading.

Keywords SMAs • Phase transformation • Infrared thermography • Cyclic loading • Mechanical dissipation • Heat sources

2.1 Introduction

Shape memory alloys (SMAs) have peculiar thermomechanical properties. Superelasticity and memory effect are the most famous ones. The high reversibility of the austenite-martensite (A-M) transformation occurring in these materials is at the origin of their macroscopic properties. The present work proposes to assess the low level of irreversibility of the stress-induced transformation in Cu-Zn-Al SMAs by using infrared (IR) thermography. Specimens featuring different chemical compositions were prepared. The objective is to measure the mechanical (intrinsic) dissipation in specimens subjected to cyclic uniaxial loading at ambient temperature. The paper is organized as follows. The manufacturing procedure to obtain the specimens is first described. The experimental set-up and the data processing are then detailed. Preliminary tests are then presented: monotonic tensile test and natural return to ambient temperature. Results obtained for the cyclic tests are finally presented and discussed.

2.2 Experimental Conditions and Processing

The specimens were copper-based polycrystals. Materials were first elaborated in a standard induction furnace. Parallelepipedic ingots were obtained for each composition. The upper and lower surfaces of the ingots were machined to obtain sheets, nearly 4 mm in thickness, with flat and regular surfaces. The specimens were then heated up to 750 °C and hot rolled. The resulting sheets were finally cut to obtain the specimens for the tests. All specimens were finally tempered by heating up to 750 °C and then water quenched. Metallic samples were mechanically polished in order to remove the coarse oxide layer. Square aluminum tabs were bonded at the ends of the specimens to prevent any slippage within the grips of the testing machine, see Fig. 2.1. Table 2.1 provides the chemical compositions of two specimens discussed here as well as the dimensions of the zone where IR measurements were performed. Chemical compositions were measured using an

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Fig. 2.1 Schematic view of the specimen and two reference sheets placed in the jaws of the testing machine

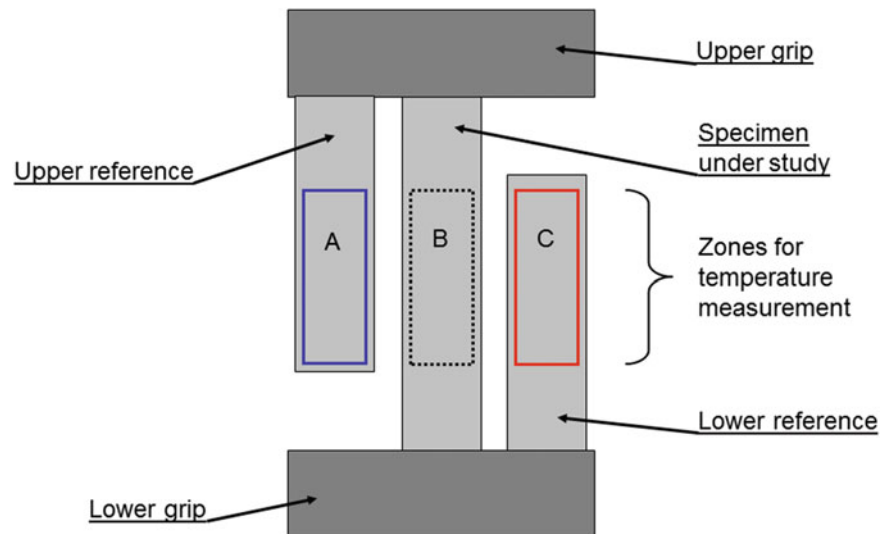


Table 2.1 Specimens under study

Specimen	State	Chemical composition (at. %)	Dimension of the gauge zone
#1	Austenitic	Cu-18.76Zn-15.42Al	$50 \times 11.03 \times 0.68 \text{ mm}^3$
#2	Martensitic	Cu-15.04Zn-18.07Al	$64 \times 10.48 \times 0.99 \text{ mm}^3$

EDS-Bruker detector with Xflash—Silicon Drift Detector (SDD) connected at a VegaTescan LMH II SEM equipment. The results were obtained from a 10 kcps signal and a work distance of 15.5 mm (supplier's recommended values). For analysis, Element List mode was used to determine the atomic percentage of Cu, Zn and Al. Compositions in Table 2.1 correspond to average values (measurement repeated twenty times) over on a zone of $3 \times 3 \text{ mm}^2$.

A MTS $\pm 15 \text{ kN}$ testing machine was used to apply the mechanical loading at ambient temperature. For each test, two copper reference sheets were also placed in the jaws of the testing machine (see Fig. 2.1). These references enabled us to extract properly the temperature change in the specimen under study (Zone B) due to mechanical loading only. In practice, temperatures in the two references (Zones A and C) were taken into account to remove parasitic effects: change in ambient temperature, change in the temperature of the grips of the testing machine (in particular the loading grip), reflection due to environment, etc. The dimension for the three zones was $50 \times 11 \text{ mm}^3$. The specimens, the two reference sheets, as well as the background, were painted in black to maximize the thermal emissivity of the thermal scene. A CEDIP Jade III-MWIR camera featuring a noise equivalent temperature difference of about 20 mK was used for temperature measurements. Note that the averaging operation over Zones A, B and C enabled us to improve the resolution of the temperature measurement. In practice, the resolution which can be reached by this averaging operation is of some mK.

All tests were performed as follows. After placing the specimen and its two references in the jaws of the testing machine, a waiting time was applied to ensure that thermal equilibrium was reached. A cyclic force-controlled loading was then applied. The loading frequency was 2 Hz. It consisted of blocks of 1200 sinusoidal cycles (i.e. 10 min) with increasing amplitudes by step of 100 MPa, up to specimen failure. The ratio between maximum and minimum forces was equal to 0.1 for all the blocks.

The acquisition frequency of the temperature fields was equal to 0.5 Hz with each recorded image, corresponding to the average of the temperature fields over 2 s captured à 100 Hz. This procedure enabled us to reduce both the size of the recorded files, and to extract the mean trend of the temperature variation.

For the present study, we applied a so-called 0D approach. This approach can be found for instance in [1–3]. It requires the use of thin specimens in such a way that the surface temperature field is representative of the temperatures in the thickness. It also requires that the heat sources produced or absorbed by the material due to stretching are homogeneous in the useful zone of the specimen. This hypothesis is reasonable for specimens featuring a constant section along the useful length, at least if there is no localization. The 0D approach was used in the present study because of very small temperature changes obtained during the cyclic tests, requiring a strong spatial averaging to improve the measurement resolution. Let us define by $\Theta(t)$ the average temperature change in time t over gauge Zone B. The heat source variation was deduced using a 0D version of the heat equation:

$$\frac{d\Theta}{dt} + \frac{\Theta}{\tau} = s \quad (2.1)$$

where s is the heat source divided by the product of the density and specific heat of the material. This quantity, expressed in °C/s or K/s, will be named “heat source” in the following for the sake of simplicity. Parameter τ is a time constant characterizing the heat exchanges of Zone B with its environment.

The heat source produced or absorbed by a material subjected to mechanical loading is composed of a quantity, which is related to thermomechanical couplings (e.g. thermoelastic coupling) as well as a quantity related to mechanical irreversibility. The latter is referred to as *mechanical dissipation* or *intrinsic dissipation*. The calorific energy corresponding to the thermomechanical couplings is null over a thermodynamical cycle. As each recorded thermal data here corresponds to the average of the temperature changes over 4 cycles ($2 \text{ s} \times 2 \text{ Hz}$), the processing enabled us to directly extract the mechanical dissipation.

2.3 Preliminary Tests

Before performing the cyclic tests, we performed two preliminary tests for each composition: a monotonic tensile test at ambient temperature, and a natural return to ambient temperature. The former provided the stress-strain response of the material, while the latter enabled us to identify the value of the time constant τ in Eq. (2.1).

Figure 2.2 shows the stress-strain curves at a stress rate of 100 MPa/s for the two specimens. For specimen #1, a linear response is first observed (corresponding to the elasticity of the austenite). From about 200 MPa, an austenite-to-martensite ($A \rightarrow M$) transformation occurred. For specimen #2, a martensite reorientation process occurred while loading.

Figure 2.3 shows the variation of the temperature change Θ for both tests. For specimen #1, the temperature change is first negative due to thermoelastic coupling. Then temperature strongly increases due to the latent heat production (exothermic $A \rightarrow M$ transformation). Mechanical dissipation due to plasticity probably also contributes to the heating in the last part of the test. For specimen #2, temperature changes are smaller because martensite reorientation is not associated to latent heat production. As for specimen #1, first temperature decreases due to thermoelastic coupling which is predominant. Then it increases due to a stronger mechanical dissipation associated to irreversibilities in the martensite reorientation process, and probably also to plasticity in the last part of the test.

Figure 2.4 shows the variation of the temperature change during a natural return to ambient temperature. The time constant τ was estimated to 9.5 s for specimen #1 and to 30 s for specimen #2. The difference can be explained by the difference in thickness of the specimens (see Table 2.1). Indeed, the thicker the specimen, the lower the time constant τ .

Fig. 2.2 Tensile test at 100 MPa/s up to specimen failure: stress-strain curve

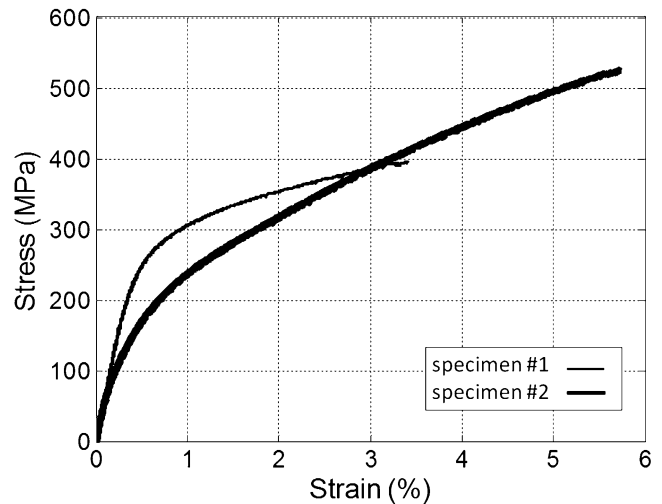


Fig. 2.3 Tensile test at 100 MPa/s up to specimen failure: temperature change vs. time

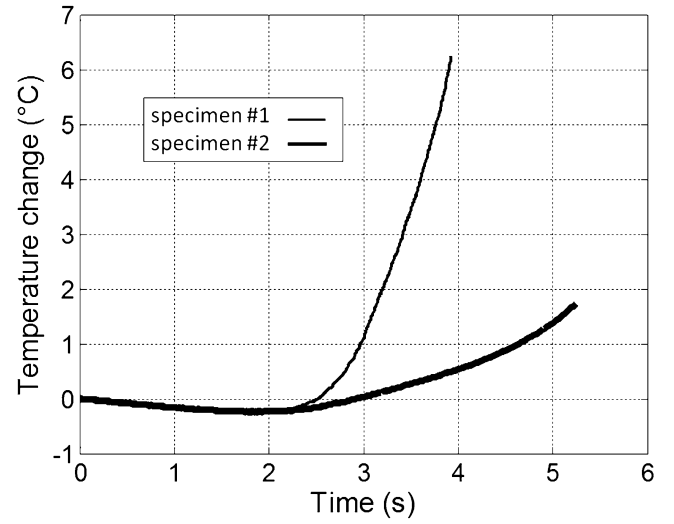
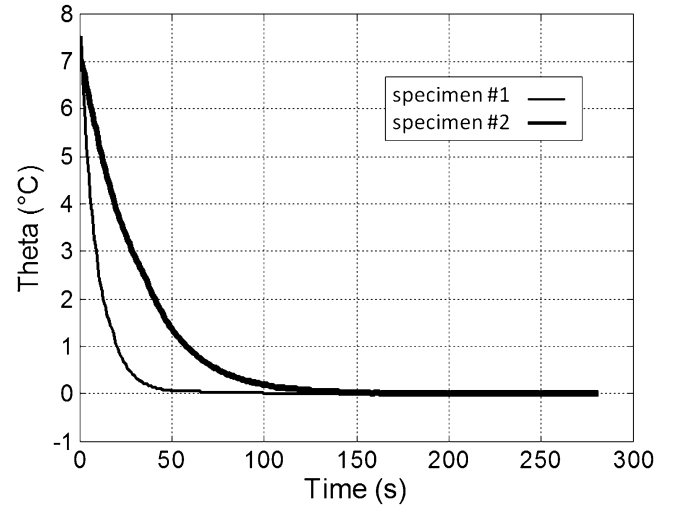


Fig. 2.4 Natural return to ambient temperature: temperature change vs. time



2.4 Results

Figure 2.5 shows the maximum and minimum values of the strain during the fatigue test for specimen #1. This specimen failed during the third block. Within each block, the maximum and minimum strains evolved over the mechanical cycles. These strains quickly stabilized in the first two blocks. The variation of these maximum and minimum strains is the consequence of mechanical irreversibilities, whose mechanical dissipation is the calorific signature.

Let us recall that the heat source is a priori composed of three parts: the thermoelastic coupling term, the latent heat source due to phase transformation, if any, and the mechanical dissipation (associated to an irreversibility in the phase transformation or in the martensite reorientation process, and to plasticity). Under cyclic loading, the *stabilized* temperature change due to thermoelastic coupling is equal to zero. Similarly, the *stabilized* temperature change due to a cyclic $A \leftrightarrow M$ transformation, if any, is also equal to zero. The mechanical dissipation is a quantity which is always positive. As a consequence, the *stabilized* temperature change obtained during the experiments is expected to be due to the mechanical dissipation only [3].

Figure 2.6 shows the variation of the temperature change during the first two blocks for specimen #1. At the beginning of each block, temperature immediately decreases as a consequence of the thermoelastic coupling or $A \rightarrow M$ transformation (let us recall that the mechanical loading started by a stress increase). Temperature increases for about 1 min and stabilizes above the ambient temperature. The order of magnitude of the temperature change in the stabilized regime is 10 mK. It is worth noting that the averaging operations mentioned above enable us to observe a stabilized temperature change of this order of magnitude for about 9 min. Mechanical dissipation is deduced from the temperature change in the stabilized regime by dividing by the time constant τ . Table 2.2 provides the values which are obtained for specimen #1. For each block, three

Fig. 2.5 Maximum and minimum values of the strain during the fatigue test for specimen #1

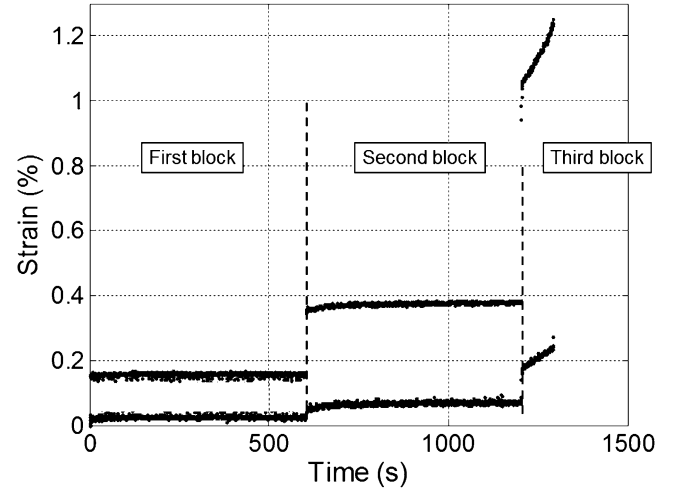


Fig. 2.6 Temperature change during the first two blocks for specimen #1

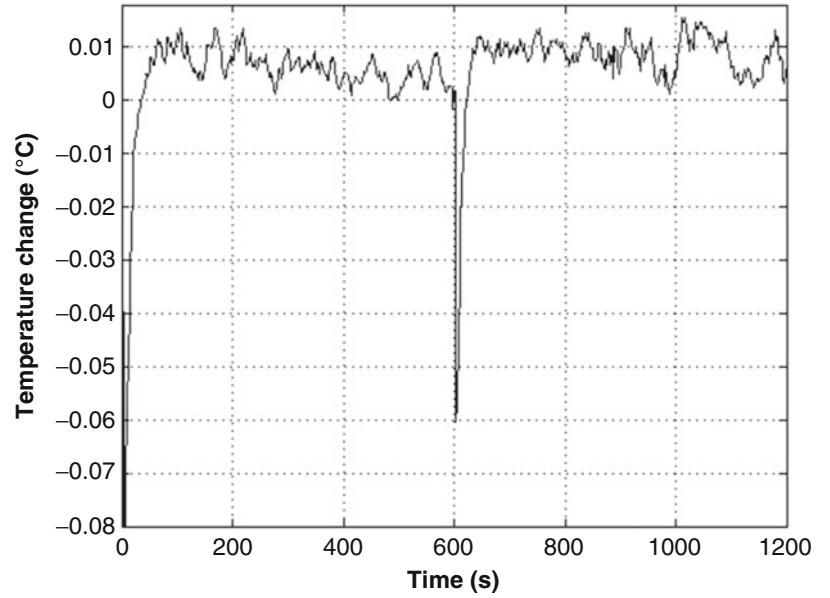


Table 2.2 Mechanical dissipation during the cyclic test

		Specimen #1
First block $\sigma_{min} = 10$ MPa $\sigma_{max} = 100$ MPa	S_{mean} (mean value)	0.67 mK/s
	S_{max} (max)	0.91 mK/s
	S_{end} (at the end of the block)	0.46 mK/s
Second block $\sigma_{min} = 20$ MPa $\sigma_{max} = 200$ MPa	S_{mean}	0.97 mK/s
	S_{max}	1.02 mK/s
	S_{end}	≈ 1 mK/s
Third block $\sigma_{min} = 30$ MPa $\sigma_{max} = 300$ MPa	S_{mean}	—
	S_{max}	—
	S_{end}	—

quantities are given: the maximum mechanical dissipation, the mechanical dissipation at the end of the block and a mean value over the 9 min time period. It can be noted that the mechanical dissipation slightly decreases over the cycles. The comparison with the results obtained for the second specimen shows that the chemical composition, as well as the nature of the phase which is involved (martensite or austenite), influence the mechanical dissipation which is produced by the specimen during the cyclic mechanical loading.

2.5 Conclusion

SMAAs are characterized by a very high reversibility of the solid-to-solid phase transformation. This study proposes an experimental procedure based on infrared thermography to assess the mechanical dissipation in SMA specimens subject to mechanical cyclic loading. Tests were performed on Cu–Zn–Al specimens in both the austenitic and the martensitic states, each of them featuring a specific thermal response. In particular, different values of the mechanical dissipation were measured, thus revealing different levels of mechanical irreversibility.

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Residual Stress, Thermomechanics & Infrared Imaging,
Hybrid Techniques and Inverse Problems, Volume 9
Proceedings of the 2016 Annual Conference on
Experimental and Applied Mechanics
Quinn, S.; Balandraud, X. (Eds.)
2017, VIII, 198 p. 170 illus., 131 illus. in color.,
Hardcover
ISBN: 978-3-319-42254-1