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The Temperature Effect on the Thermo-Mechanical Behaviour in Shape Memory Polycrystalline CuZnAl Alloy

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Abstract: The goal of this work is the study of the pseudoelastic behaviour of shape memory polycrystalline CuZnAl alloy. To this end, pseudoelastic tests were carried out using a machine that is specific to Shape Memory Alloys (SMA) (the four point bending machine). The tests were made at a strain controlled regime (constant maximum strain) in a significant temperature range i.e., [25, 105°C]. The electrical resistivity (because of its sensitivity to structural changes during phase transitions at the solid state) was also used to characterize CuZnAl. In particular, it was used to determine the points of direct and reverse martensitic transformation. The obtained result shows that at lower temperatures a reorientation of the martensite variants takes place, whereas at high temperatures a phenomenon of germination and growth of martensite under stress is observed. It is found that, in agreement with what is reported in the literature, the value for the Young modulus differs drastically for the two martensitic and austenitic states. It is also shown that both maximum and critical stresses increase with increasing test temperature and that, during a mechanical cyclic and for a given temperature, the residual strain increases according to a phenomenon of defect accumulation and decreases with increasing test temperature.

Key words: Shape Memory Alloys (SMA), Cu-Zn-Al, thermoelastic martensitic transformation, Electrical Resistivity (ER), pseudoelastic effect, four points bending

INTRODUCTION

Shape Memory Alloys (SMA), also called «intelligent materials», are new materials that are particularly known for their unusual thermo-mechanical properties: Shape memory effect, pseudoelastic effect, superelastic effect, rubbery effect. These remarkable properties, mainly due to the thermoelastic martensitic transformation (Van, 2004), make it that these alloys are taking more and more importance in the technological field: aerospace, biomedical, robotics, agriculture (e.g., used as moisture absorbers to protect seeds) (Huang, 2002). The martensitic transition can occur by a simple temperature sweeping or by stress application in a certain temperature range. It is reversible, but includes a hysteresis of about ten degrees (10°C) and a spreading out of 20°C (Torra *et al.*, 2001; Shi *et al.*, 1998).

In this study, we have studied the thermo-mechanical behavior of the polycrystalline CuZnAl alloy in a broad range of temperatures: from 25 to 105°C. The study is mainly based on electrical resistance measurements (four probe method) and on mechanical tests carried out using a machine that was specifically designed for shape memory alloys (the four point bending machine).

EXPERIMENTAL PROCEDURE

Specimen preparation: The low Al content (4wt %) ternary CuZnAl alloy, was manufactured by the Tréfimétaux company (France), under the form of a 2 mm-thick sheet.

A set of (1.2 * 4.9 * 7.6) mm^3-dimensioned plates was obtained through cutting and rolling. The full set of samples is submitted to a standard heat treatment before any measurement is made. This is according to the scheme given in (Table 1):

Experimental techniques: In this research, we have used two different characterization techniques: the electrical resistivity-related four-probe technique and the four-point bending method.

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Table 1: Heat treatment scheme

Treatments	Temperature (°C)	Time (mn)	Drank
Homogenization	850	20	Homogenization in β phase
Qquenched	20	-	To stabilize the β structure
Annealing	100	30	Elimination of the quenched vacancies

Electrical resistance measurement: This technique was mainly used to determine the transformation temperatures during the phase transition at the solid state and thus to determine the temperature range for the mechanical tests. The principle of this method is based on a measurement of the sample electrical resistivity variations during the transformation. Effectively, since the martensitic transformation involves weak dimensional variations only, the resistance variations of are essentially due to those of the sample resistance.

The four point bending method: The mode of request used in our tests on the CuZnAl alloy for the thermo-mechanical characterization is a specific machine: the four point bending machine. For this raison, an apparatus that is specific for SMA was designed and developed at the GEMPPM laboratory (INSA, Lyon). The apparatus allows applying a homogeneous stress, within the sample, whose values are determined by simple relations of resistance of materials. Thus, with this assembly, one can estimate, during loading and unloading, the stress evolution as a function of the bend variation at different test temperatures as well as the stress evolution with temperature at different imposed strains.

RESULTS AND DISCUSSION

Points of transformation: The phase transformation temperatures of the studied sample were deduced from electrical resistance measurements. Figure 1 gives a typical representation of the evolution of the electrical resistance with temperature as well as the method for the determination of the transformation points.

An increase in electrical resistance, characteristic of the direct transformation (1) (austenite → martensite), is observed on cooling whereas the reverse transition (martensite → austenite), characterized by a decrease in electrical resistance, is observed on heating. The shape of the obtained curve for the electrical resistance is similar to that reported, in the literature, for the case of copper based alloys (Benchiheub *et al.*, 2000; Airoldi *et al.*, 1997; Belkahilacl *et al.*, 1993; Jourdan *et al.*, 1999; Gonzalez, 2002). In the case of our alloy, the estimated values for the Transformation Temperatures (TT) are as follows (Table 2).

Table 2: Values of the transformation temperatures obtained for our alloy

	M_S	M_F	A_S	A_F
TT (°C)	65	53°C	76°C	81°C

Ms = Martensite start, M_F = Martensite finish, A_S = Austenite start, A_F = Austenite finish

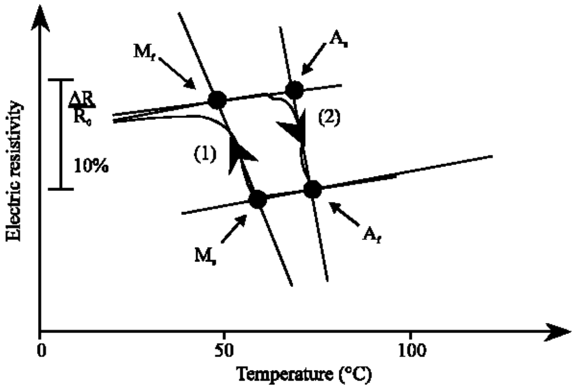

Fig. 1: Typical curve of the variation of electrical resistivity as a function of the martensitic transformation temperature characteristics

Pseudoelasticity: Pseudoelasticity is a nonlinear behavior that is obtained during an isothermal solicitation in the martensitic state (Vivet *et al.*, 2001). Pseudoelastic cycles (σ-ε) were performed, using a four-point bending machine, at various test temperatures and for a strain controlled regime (maximum strain applied to the sample is constant for all mechanical tests). Figure 2 represents the stress-strain cycles (σ-ε) obtained at various temperatures and for a same Imposed Maximum Strain ε_{max} (IMS). In this figure, we note that, in connection with the structural state of the sample which can be either Martensitic (M), Austenitic (A), or mixed (A+ M), the shape of the curves varies with varying test temperature.

The application of the stress with the sample in the martensitic state ($T \leq MF$) led to a reorientation of the martensite variants in the direction of the applied stress. During unloading, we observe a partial return of the martensite variants and a permanent strain (noted ε_r) that persists even for a zero stress. This residual strain is due to a plastic strain generated by the accommodation phenomena of the martensite variants. With the test temperature equal to 100°C, the sample is in an austenitic state and presents a stress-strain curve that is different from that obtained at 25°C for which the sample is in a martensitic state. The application of the stress with the sample in its austenitic state causes the under stress transformation to the martensite state, however as one may notice, the sample recovers its initial state immediately after suppressing the stress, this is superelasticity.

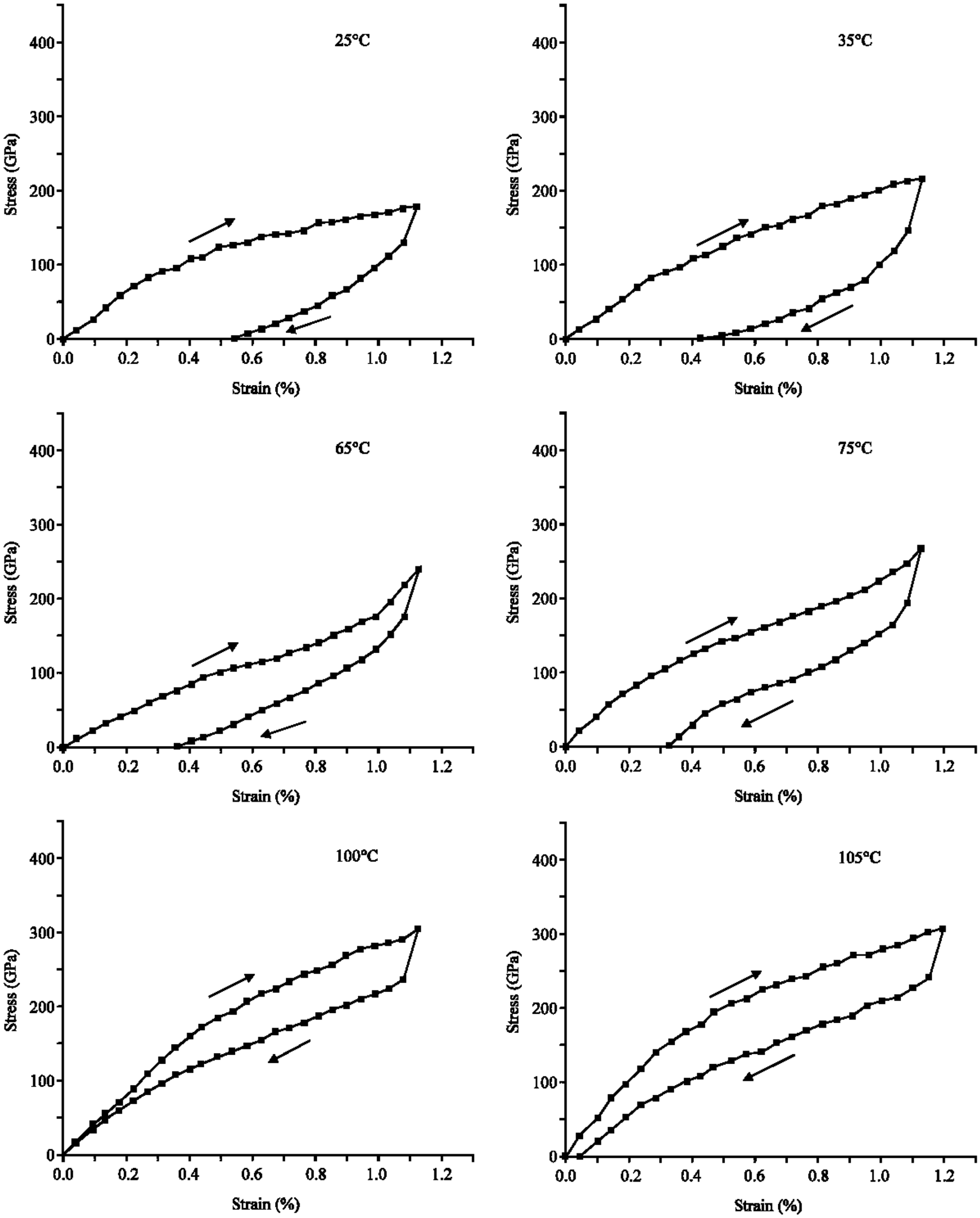

Fig. 2: Pseudoelastic curves (stress-strain) at various temperatures

The obtained curves (σ-ε) are similar to those, obtained for different modes of solicitation (Siredey and Eberhardt, 2000; Pons *et al.*, 1999; Balo *et al.*, 2002; Pena *et al.*, 2002), that are reported in the literature. Moreover, we note that the maximum stress (σ_{max}) needed to get the IMS increases with increasing test temperature.

Young modulus: The test-temperature dependence of E, the Young modulus, for the various structural states of the specimen is given in (Fig. 3). We observe three distinct fields on this curve. In the Low Temperature (LT) (martensitic state) and the High Temperature (HT) (austenitic state) regions, the Young module is practically

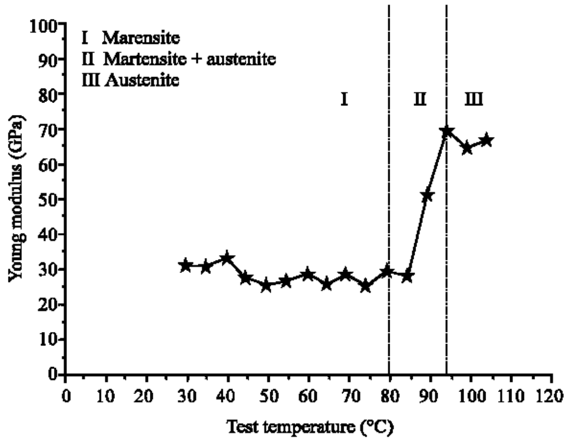

Fig. 3: Evolution of the Young modulus (E) as a function of the test temperature

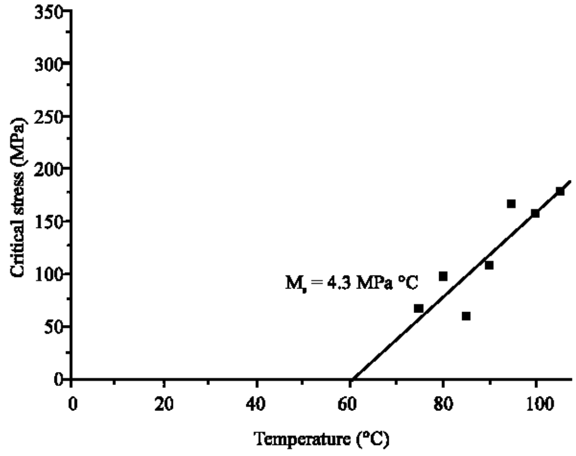

Fig. 4: Metastable state diagram of M_s

constant; E ≈ 30 GPa at LT and E ≈ 70 GPa at HT. These results are in agreement with those given in the literature (Orgeas *et al.*, 2004 and Huang, 2004).

Diagram of state σ-T: A plot of the metastable state diagram σ-T, represented in (Fig. 4), was deduced from the σ-ε curves obtained at various temperatures. The σ-T curve is well represented by the Clausius Clapeyron law (for temperatures higher than A_f). The critical stress σ_c increases with increasing test temperature (as, approximately, a straight line with a slope of ≈ 4.3 MPa/°C). This result is close to that reported in the literature for other modes of solicitation such as: traction, torsion etc. (Benchiheub *et al.*, 2000; Arneodo and Ahlers, 2003; Kuslov *et al.*, 2002; Fernandez *et al.*, 2003).

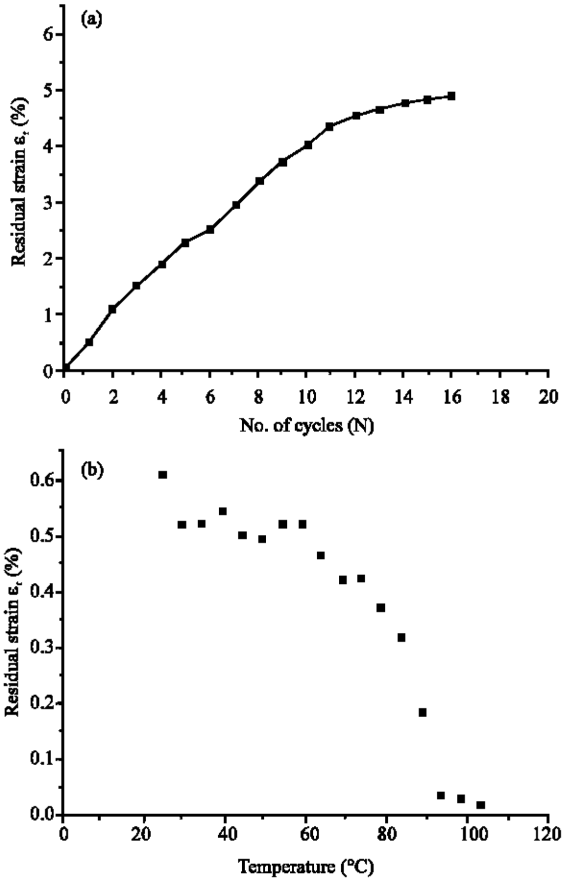

Fig. 5: Evolution of the residual deformation (a) as a function of the number of cycles N (b) as a function of the test temperature

Residual strain: We also deduced, from the σ-ε curves, the evolution of the residual strain as a function of the test temperature (Fig. 5b) and as a function of the number of cycles (Fig. 5a). We may note, from (Fig. 5), that the residual strain ε_r decreases with increasing test temperature and increases with increasing number of cycles. This is probably due to a phenomenon of defect (dislocations) accumulation within the sample during mechanical cycling. In the martensitic state-related temperature region, the residual strain is very significant and is the martensite under stress related plastic strain, this is the pseudoelastic effect. At high temperature, on the other hand, the residual strain is practically absent because the alloy is deformed elastically and the phase transformation is reversible: this is the superelastic effect.

CONCLUSION

- The test temperature has an important influence on the general aspect of the σ-ε curve: both pseudoelastic and superelastic effects are present. The first of these is observed at low temperatures and the second at high temperatures.

- The critical stress that is necessary to induce the first martensite variant under stress needles increases as the test temperature is increased.
- The maximum stress needed to get the imposed maximum strain increases with increasing test temperature.
- The observed Young modulus for the studied alloy has a value of 70 GPa at the austenitic state and a value of 30 GPa at the martensitic state.
- The residual strain decreases with increasing test temperature during a cycle (load-unload) and increases with the number of cycles by a phenomenon of defect accumulation during mechanical cycling in the martensitic phase.

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