

**INTERNAL FRICTION STUDY OF STRESS-INDUCED MARTENSITIC TRANSFORMATION IN Cu-Zn-Al SHAPE MEMORY ALLOYS**

J. STOIBER, J.-E. BIDAUX and R. GOTTHARDT

*Institut de Génie Atomique, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

**Abstract** - The method of internal friction has been used for studying stress-induced martensitic transformation in Cu-Zn-Al polycrystals. The observed internal friction spectrum for a given pseudoelastic cycle is a unique, non-linear function of the transformation rate, and is independent of the actual amount of transformed volume. The internal friction values decrease with increasing stress cycling temperature, indicating that only at sufficiently high temperatures above  $M_s$  is a perfectly oriented martensitic structure obtained.

1.- Introduction.

The martensitic phase transformation in Cu-Zn-Al shape memory alloys is accompanied by a transformation hysteresis. For technical applications, e.g. if reliable shape responses of a two-way memory actuator are required, it is important to control the shape of the transformation hysteresis (i.e. its width and its slope). An important problem for the hysteresis stability arises when small temperature and stress fluctuations occur in the two-phase regime. Typical phenomena like transformation creep, degradation of shape memory, and martensite stabilization have been observed during practical applications.

A detailed analysis of hysteresis instabilities occurring in the two phase region during *temperature-induced* martensitic transformations has been presented in [1]. Internal friction (IF) measurements in combination with transmission electron microscopy (TEM) in situ observations have shown that the microstructure of a thermoelastic martensite like in Cu-Zn-Al alloys is subjected to modifications during small temperature cycles. Reorientation between different martensitic variants together with rearrangement of the stacking sequence inside an individual martensitic plate, locally reduces high internal stresses and stabilizes the martensitic phase with respect to the austenitic one.

In this paper, we present first results about *stress-induced* transformations or pseudoelastic cycling in Cu-Zn-Al alloys studied by the method of internal friction. The significance of this work is twofold:

First, this type of measurement can give a direct relationship between the macroscopic and microscopic transformation hysteresis behaviour. The area enclosed by the  $\sigma$ - $\epsilon$  curve is a measure of the total dissipated energy during one transformation cycle while the value of internal friction,  $Q^{-1}$ , characterizes the energy locally dissipated at discrete points of the  $\sigma$ - $\epsilon$ -curve:  $Q^{-1} = \frac{1}{2\pi} \cdot \frac{\Delta W}{W}$ , where  $\Delta W$  is the energy dissipated during one oscillation cycle.

Second, during stress-induced transformation, the influence of interactions between differently oriented variants is reduced since only those variants which give the maximum amount of strain in the direction of the applied stress will form in each grain. From the point of view of internal friction theory, it is therefore interesting to compare the  $Q^{-1}$ -behaviour of thermally and stress-induced transformations. The practical aspect of this investigation concerns the problem of hysteresis instabilities occurring during stress-induced transformations.

2.- Experimental.

The internal friction measurements have been performed in an inverted torsion pendulum, where  $Q^{-1}$  can be measured simultaneously with other physical parameters like resonance frequency ( $f$ ), electrical resistance ( $R$ ), length change of the specimen ( $dL$ ), and torsion angle. The pendulum has been modified in such a way that, in addition to temperature programs, controlled tensile stress variations can be applied to the specimen, see figure 1.

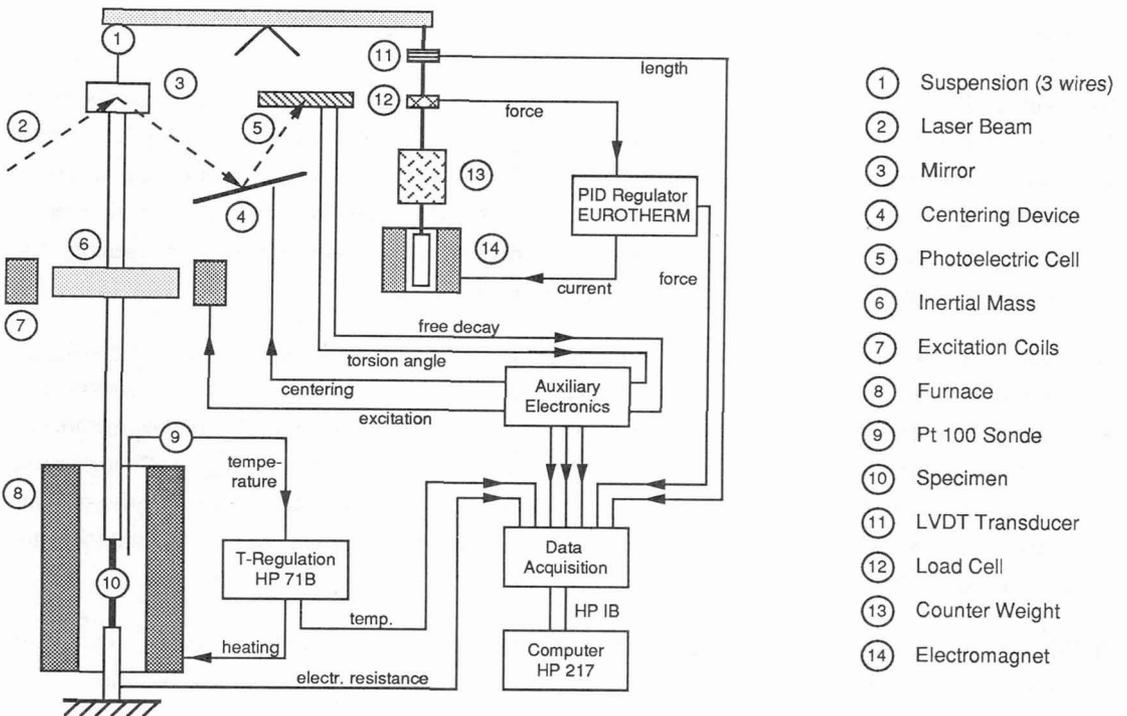


Fig.1.- Schematic representation of the modified pendulum

The stress application device consists of an electromagnet, which is connected to a counter weight and applies a tensile force to the specimen proportional to the electrical current. The force ( $F$ ) is measured by a load cell, which is fixed on the upper part of the counter weight and is controlled by the D.C. supply of a commercial PID regulator. The maximum force of this system is about 50N and the stability is at least  $\pm 0.02\text{N}$ . The regulator can be programmed to perform ramps with any constant force rates. A LVDT (linear voltage differential transformer) indirectly detects changes in the length of the specimen ( $dL$ ) by the displacement of the counter weight. The  $\sigma$ - $\varepsilon$  curves have been calculated with the initial cross section  $A_0$  and the initial length  $L_0$  of the specimen:  $\sigma = F/A_0$  and  $\varepsilon = dL/L_0$ .

Specimens ( $15 \times 1.75 \times 0.38 \text{ mm}^3$ ) of a Cu-19.3Zn-7.2Al (wt.%) alloy with  $M_s = 206\text{K}$  have been studied. The low  $M_s$ -temperature has been chosen in order to avoid stabilization effects in the martensite which evidently influence the overall hysteresis behaviour [2]. The applied oscillating strain amplitude  $\varepsilon_{\text{osc}}$  has been kept constant for all measurements ( $\varepsilon_{\text{osc}} = 2.5 \cdot 10^{-5}$ ).

### 3.- Results and discussion.

#### 3.1- Internal friction spectrum during a pseudoelastic loop.

Since it is the first time that pseudoelastic loops have been studied by means of internal friction, we begin with the general  $Q^{-1}$ -behaviour during such a transformation for  $d\sigma/dt = \text{const}$ . Figure 2 shows the  $\sigma$ - $\varepsilon$  curve and the corresponding spectrum of  $Q^{-1}$  and  $f$  as a function of  $\sigma$ , measured at  $T=215\text{K}$ . This kind of presentation has been chosen in order to have an adequate comparison with the usual  $Q^{-1}(T)$ -plot during thermally induced transformation. Qualitatively,  $Q^{-1}(\sigma)$  shows the same characteristics as  $Q^{-1}(T)$ , namely:

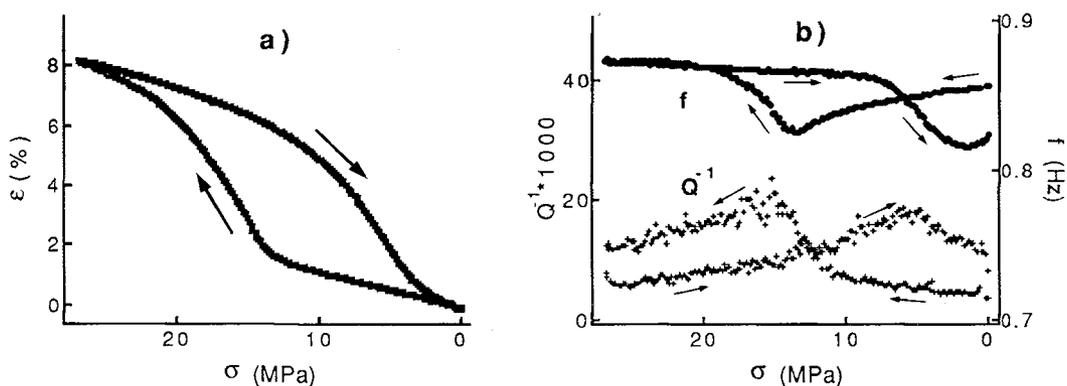


Fig.2.-  $\sigma$ -  $\varepsilon$  curve (a) and  $Q^{-1}$ ,  $f$  as a function of  $\sigma$  (b),  $T=215\text{K}$ ,  $\dot{\sigma}=30\text{MPa/h}$ .

- A  $Q^{-1}$ -maximum is found during forward and reverse transformation corresponding to a minimum of the resonance frequency (fig.2b).
- The  $Q^{-1}$ -peak has a strong transitory character, as can be seen from the dramatic decrease of  $Q^{-1}$  when  $\dot{\sigma}$  is stopped and the measurements are conducted for constant  $\sigma$  (fig.3). This we call  $\dot{\sigma}$ -effect.

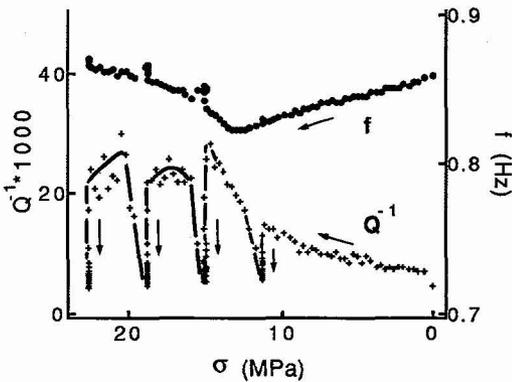


Fig.3-  $Q^{-1}$  and  $f$  as a function of  $\sigma$  when  $\dot{\sigma}$  is stopped at different  $\sigma$ -values during loading,  $T=215K$ .

In analogy with the  $\dot{T}$ -effect of thermal transformations (see for example [3]), it is reasonable to define the  $\dot{\sigma}$ -effect also by the transitory part of internal friction,  $Q^{-1}_{Tr}$ :

$$Q^{-1}_{Tr} = Q^{-1}_{tot} - Q^{-1}(\dot{\sigma}=0),$$

where  $Q^{-1}_{tot}$  is the total amount of the measured internal friction.  $Q^{-1}_{Tr}$  has been related to the amount of transformed volume during one oscillation cycle and is therefore dependent on the transformation rate  $dm/dt$ , which is measured by changes in the electrical resistance,  $dR/dt$ .

In [1], it has been shown that during *temperature-induced* transformations in Cu-Zn-Al alloys two different  $dR/dt$ -dependencies of  $Q^{-1}_{Tr}$  exist. For a given transformation rate,  $Q^{-1}_{Tr}$  is significantly higher at the end of the transformation than in the beginning. This has been attributed to an increasing martensite-austenite interface density and to interactions between different martensitic variants.

For a *stress-induced* transformation, fig.4 shows the dependence of  $Q^{-1}_{Tr}$  and  $dR/dt$  on  $\sigma$ . It can be seen that both parameters have a maximum at the same stress level. However, a proportionality between  $Q^{-1}_{Tr}$  and  $dR/dt$  does not exist, since both curves cross each other. Plotting  $Q^{-1}_{Tr}$  as a function of  $dR/dt$ , a non-linear behaviour is therefore observed (fig.5). It is worthwhile mentioning that the  $Q^{-1}$ -values on both sides of the forward and of the reverse transformation peak (fig.4) establish a common  $Q^{-1}_{Tr}(dR/dt)$  curve. Furthermore, the curves at different stress rates overlap, indicating that  $Q^{-1}_{Tr}$  is only dependent on the transformation rate and not on the actual amount of transformed volume or on the extend of the transformation. Work is in progress in order to explain the physical mechanism giving rise to this type of damping behaviour.

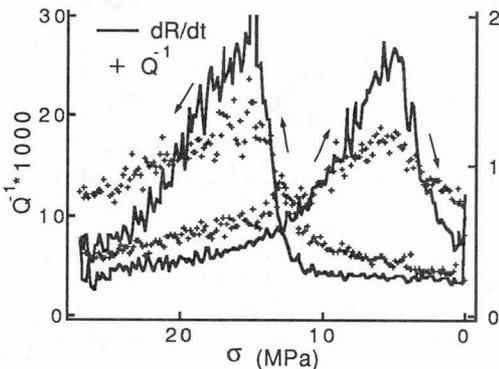


Fig.4.-  $Q^{-1}$  and  $dR/dt$  as a function of  $\sigma$ ,  $T=215K$ ,  $\dot{\sigma}=30MPa/h$ .

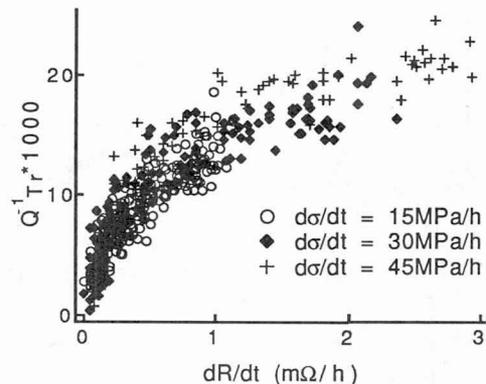


Fig.5.-  $Q^{-1}_{Tr}$  as a function of  $dR/dt$  for different  $\dot{\sigma}$  at  $T=215K$ .

### 3.2- Temperature dependence of a pseudoelastic loop.

Fig.6a shows the  $\sigma$ - $\epsilon$  curves for three different temperatures ( $T > M_s$ ,  $M_s = 206\text{K}$ ). The temperature dependence of the critical stress,  $\sigma_c$ , necessary to induce the transformation is about  $2\text{MPa/K}$ , which is a normal value for the  $\beta_1 \rightarrow \beta_1'$  transformation in Cu-Zn-Al polycrystals [4]. One can see that only at  $225\text{K}$  is a perfect pseudoelastic behaviour obtained, while for the other temperatures a certain amount of permanent deformation remains after unloading, due to the hysteresis effect. Superposition of the respective curves indicates that the shape and the enclosed areas of (1) and (2) are quite similar. On the other hand, comparing the first part of the retransformation, curve (3) reveals a larger stress hysteresis than (1) and (2). The IF-behaviour corresponding to these stress cycles is illustrated in fig.6b by the  $Q^{-1}_{Tr}$  ( $dR/dt$ ) diagrams. From this figure, it is evident that an increase of the stress-cycling temperature decreases the  $Q^{-1}$ -values, with the biggest difference observed between  $205\text{K}$  and  $210\text{K}$ .

Although these are only preliminary results, they suggest that the martensite structure obtained during stress induced transformations is dependent on the stress level which precedes the transformation:

For low stresses ( $T$  near  $M_s$ ), the relative amount of internal stresses created during transformation (e.g. at grain boundaries) is sufficiently high to induce variants oriented in directions other than the applied tensile stress. The elastically stored energy accelerating the reverse transformation is then lowered, leading to a higher macroscopic hysteresis. With respect to the microstructure, differently oriented martensitic variants interact with each other by the formation and movement of martensite-martensite interfaces. The IF-measuring stress has consequently more possibilities to interact with transforming variants and the  $Q^{-1}$ -values increase. If the applied tensile stress is very high ( $T$  far above  $M_s$ ), the influence of internal stresses on the orientation of the transforming variants decreases and the amount of the locally dissipated energy (or  $Q^{-1}$ ) also decreases.

Therefore, a direct relation between the macroscopic and microscopic hysteresis effect can be established: A larger macroscopic hysteresis produces higher IF-values. Furthermore, the IF-behaviour provides information about the microscopic mechanisms which control the overall hysteresis.

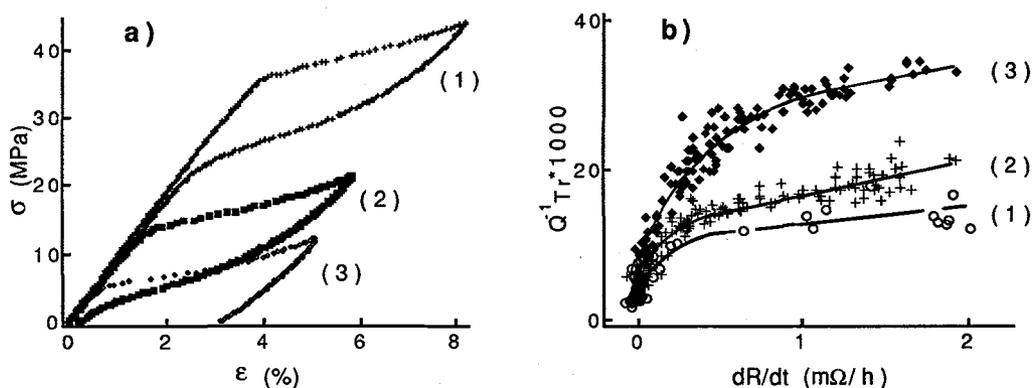


Fig.6.-  $\sigma$ - $\epsilon$  curves (a) and  $Q^{-1}_{Tr}$  as a function of  $dR/dt$  (b) for different temperatures:

(1)  $T=225\text{K}$ , (2)  $T=215\text{K}$ , (3)  $T=210\text{K}$ .

#### 4.- Summary.

- An inverted torsion pendulum has been modified in such a way that controlled tensile stress variations can be performed in order to study stress induced martensitic transformations and pseudoelastic loops in shape memory alloys.

- The IF-spectrum measured during stress cycling in a polycrystalline Cu-Zn-Al alloy shows similarities to the one obtained during thermal cycling, i.e. a  $Q^{-1}$ -maximum is observed corresponding to a minimum of the resonance frequency. Furthermore, a  $\dot{\sigma}$ -effect has been observed similar to the  $\dot{T}$ -effect and is defined by the transitory part of the internal friction,  $Q^{-1}_{Tr}$ . For a given pseudoelastic cycle  $Q^{-1}_{Tr}$  is a unique, non-linear function of the transformation rate and is independent of the actual amount of transformed volume.

- Stress cycling at various temperatures above  $M_s$  indicates a relationship between the macroscopic hysteresis behaviour and the local or microscopic hysteresis measured by means of the internal friction: A larger hysteresis creates higher internal friction values. This effect is attributed to interactions of differently oriented martensitic variants obtained when the stress cycling temperature is not sufficiently above  $M_s$ .

- The present results indicate that internal friction measurements give very useful information about the fundamental mechanisms causing the hysteresis effect during stress induced martensitic transformations.

#### References

- [1] J.Stoiber, J.Van Humbeeck, R.Gotthardt, Proceedings of the International Symposium on  $M^3D$  : Mechanics and Mechanisms of Materials Damping, Baltimore, USA, 1991, to be published in the ASTM journal.
- [2] A.Abu Arab, M.Ahlers, Acta metall., 36(9), 1988, 2627-2638.
- [3] J.-E.Bidaux, R.Schaller, W.Benoit, Acta metall., 37(3), 1989, 803-811.
- [4] K.Otsuka, H.Sakamoto, K.Shimizu, Acta metall., 27, 1978, 585-601.