

# The limiting of the response time of shape memory alloy actuators by transformation rate

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## Introduction

Shape memory alloys (SMA) are recognized as intelligent materials because they are capable to feel a change in external parameters (temperature, mechanical stress etc.) and to act (shape or recovery force change etc.) according to this change by change of their internal parameters (lattice parameters, internal energy etc.). These properties are the best conditions for their application as actuators. In the series of concurrent materials as ferromagnetic or ferroelectric ones, SMA have much greater strain and stress response [1], but much slower response time or the action frequency. The response time of SMA actuators is a sum of cooling and heating time through the characteristically temperature interval  $M_f$ - $A_f$  within that take place forward and reverse martensitic transformations that causes the action. The frequency of SMA actuator is a number of complete transformation cycles per 1 sec. This frequency is less as 1Hz [2].

Intensive investigations of the last time [2-5] focus on the increasing this frequency by means of the miniaturization of SMA actuators and of the using of more effective cooling methods, for example, by means of the thermoelectric Peltier effect [6]. On this way the frequency about 10 Hz is reached [2, 6]. Actuating frequencies up to 100 Hz are theoretical predicted by miniaturization of SMA actuators (SMA foils down to 1-2  $\mu\text{m}$ ) and conventional cooling methods [7].

It will be discussed an alternative way to increase of action frequency of SMA actuators in which the martensitic transformation could be induced by electric or magnet field instead of the thermo-inducing [8]. But there are no optimistic results on this way.

The analyze of this investigation trend shows that only the scanning rate, connected with heat transfer, will be accepted as a limiting factor for the action frequency of SMA actuators. The transformation kinetics or a possible physical limiting of the transformation rate will be not discussed and investigated. It is the aim of the present paper to investigate existence of this intrinsic limiting of the response time of SMA actuators.

## Experimental procedure

Influence of the temperature scanning rate on the hysteresis loop position ( $T_0$ ), its side ( $A_f - M_f$ ), and slope ( $\frac{dT}{dz} = \frac{A_f + M_f - A_s - M_s}{2}$ ) are investigated by the calorimetry. The transformation rate is measured on a *Cu-Zn-Al* single crystal alloy by the stress-induced martensitic transformation with a single-phase boundary.

Three component memory alloys on the *TiNi*-base (Table 1) with different kind of martensitic transformation including the transformation with invariant plane which is characterized by a very small hysteresis are used to investigate the influence of the temperature scanning rate

**Table 1.** Composition (at.%), type of transformation, characteristic transformation temperatures ( $^{\circ}\text{C}$ ), and transformation heat of the investigated alloys ( $\dot{T}=0.065\text{K/s}$ )

No., transf. type*	Ti	Ni	Pt	Au	Pd	Al	$M_s$	$A_s$	$\Delta T$	$Q$ , J/g	$T_0$ , K
0: <i>Mn-15.9at%Cu</i>	--	--	--	--	--	--	159	154.5	5.0	2.9	433.8
1: $B2 \leftrightarrow B19'$	50.0	50.0	--	--	--	--	60.0	86.0	40.8	27.8	346.0
2: (i) $B2 \leftrightarrow B19 \leftrightarrow B19'$	50.0	40.0		10.0	--	--	80.0 46.0	86.0 46.0	11.0	8.1	352.5
4: $B2 \leftrightarrow B19 \leftrightarrow B19'$	50.0	43.5	6.5	--	--	--	50.5 48.0	(60) 48.0	15.0	12.8	321.0
7: $B2 \leftrightarrow B19$ (i)	50.0	40.0	--	--	10.0	--	23.0	24.0	11.0	8.6	296.5
8: $B2 \leftrightarrow R$ $R \leftrightarrow B19'$	48.2	50.0	--	--		1.8	22.0 -75.0	23.0 -29.0	8.5 64.0	7.2 6.8	295.5 221.0

\*Results from X-ray diffraction

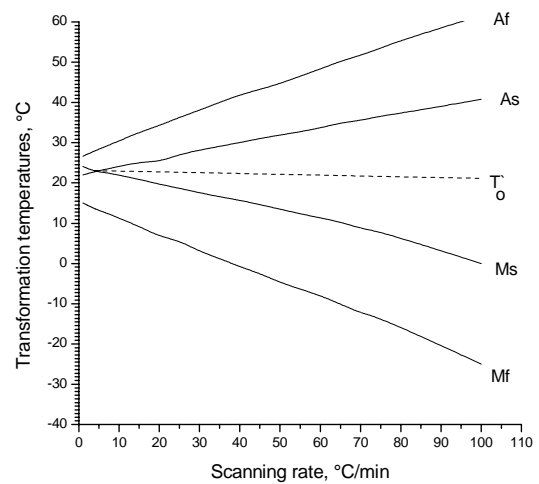
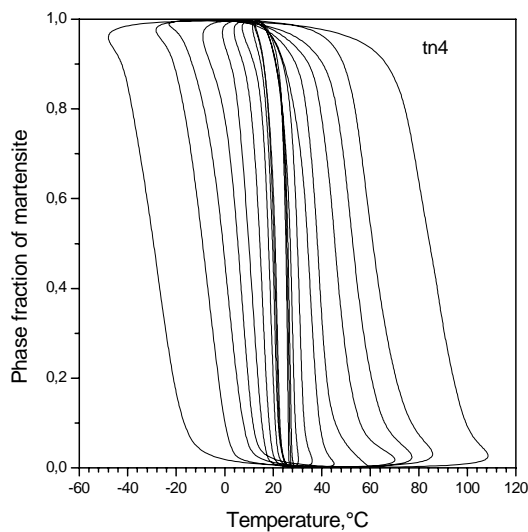
on the frequency of the stress-free thermoelastic martensitic transformation. Flat square specimens about 1mm thick and with a perimeter about 16mm were cut from the rolled band, quenched from 850 $^{\circ}\text{C}$  0.5h in cold water, and mechanical polished on the both sides. Measurements are carried out in a calorimeter DSC-7 Perkin Elmer PC-Series. The cooling of the measure-cell by fluid nitrogen allows holding the reference (environment) temperature at – 190 $^{\circ}\text{C}$ . The transformation temperatures and equilibrium temperatures (Table 1) are determined from the hysteresis loop [9]. The scanning rate is varied in the interval from 0.5 to 100K/min. The cooling with the programmed rate more as 80 K/min could not be controlled by the calorimeter.

Investigation of the transformation with a single-phase boundary is carried out on the single-crystal of *Cu-18%Zn-8%Al* shape memory alloy in an in-situ test machine [10]. The machine was placed on the light microscope that allow to observe the interface moving through the polished specimen during the strain-temperature and strain-time diagrams measurements. The sample size between grips is 2x2.5x30mm<sup>3</sup>.

## Experimental results

### Transformation frequency

Increasing of the scanning rate leads to the extension of both transformation temperature intervals and hysteresis width (Fig 1). The position of hysteresis loop, it means the equilibrium temperature, at different scanning rate remains the same. Transformation temperatures of the forward transformation linear decrease and of the reverse transformation linear increase with the scanning rate increasing (Fig. 2).



**Fig. 1.** Hysteresis loop broadening on the scanning rate from 1 up to 100 K/s (sample 7)

**Fig. 2.** Increasing of the transformation temperature interval with the scanning rate (sample 7)

The coefficient (the slope) of linear dependencies of the transformation finish temperature is greater as one of transformation start temperatures. It leads to linear dependence of transformation temperature intervals as well as to the linear increasing of the hysteresis width on the scanning rate.

The transformation rate calculated from the real measured transformation interval depends logarithmic (Fig. 3) on the scanning rate and approaches a maximal limit value about  $0.01s^{-1}$  for a complete transformation cycles.

It can be calculated the mass transformation rate with an assumption that the whole sample with the mass about 90 mg transforms to martensite at  $M_f$  and to austenite at  $A_f$ . A simple calculation results in the value 4.5mg/s for forward and 9mg/s for reverse transformation. The

frequency will be calculated through the overall time needed for a one complete transformation cycle:

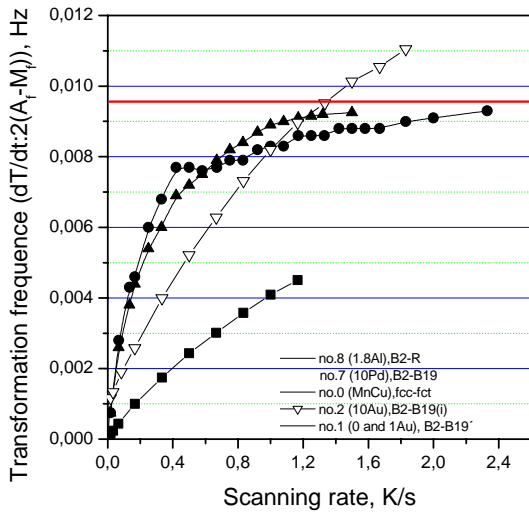


Fig. 3. Dependence of the transformation frequency of investigated samples on the scanning rate.

At the very smooth cooling of a single-crystal specimen under constant load 20N a martensite band nucleates at a one critical start temperature and grows without external temperature control (fig. 4).

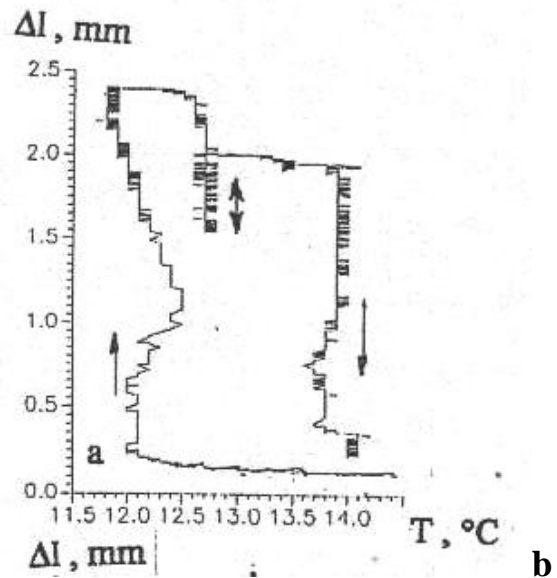
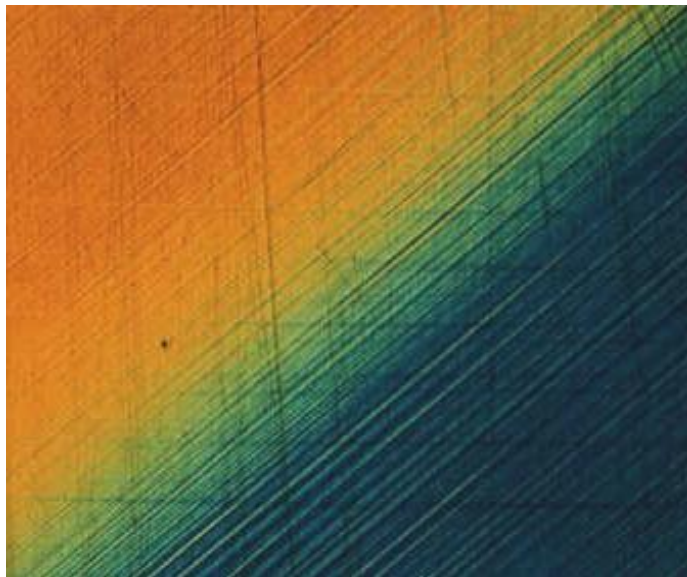


Fig. 4. The phase boundary between martensite band (yellow) and austenite (blue) (light microscopy –a) and the strain-temperature diagram by moving this boundary (b)

The thermocouple placed directly on the specimen surface in the middle of its length shows the temperature increasing about  $0.5^{\circ}\text{C}$  over the environment temperature of the sample

$$t = (A_f - M_s) / \dot{T} + t_f + (A_s - M_f) / \dot{T} + t_r \approx 100s$$

therefore is the action frequency equal about

$$f_a = t^{-1} \approx 0.01\text{Hz}$$

for all measured alloys.

### Transformation with a single-phase boundary

The transformation velocity is measured, too, for the martensitic transformation with a single phase interface on a single crystal under constant load to define the moving speed of a free martensitic boundary without of elastic interaction with inter-crystalline boundaries and other phase interface.

during the passing of the interface under the thermocouple, whereas the external temperature is holt constant. The transformation with a single-phase boundary is isotherm and shows only a small hysteresis about 1°C due to the nucleation of a martensite band. The hysteresis between two trajectories of isothermal growth of this band approach to null, as it shows the gap between the peak temperatures of exothermal and endothermal effects.

The moving rate of the single-phase boundary is measured in the light microscopy and from the plotted strain-time diagram. Thereby it was taken into account that the measured sample elongation is equal the distance between two interface positions multiplied with the martensitic shape strain caused this elongation. The calculated moving speed of the single-phase boundary is equal about 0.1mm/s for the forward transformation and only a little smaller for the reverse transformation. At the cross-section of the sample 5mm<sup>2</sup> and density 8mg/mm<sup>3</sup> the mass rate of the transformation is about 4mg/s.

### ***Heat transfer in an one complete cycle of a thermoelastic martensitic transformation***

In order to carry out a one complete transformation cycle, a SMA actuator must be once cooled and once heated through the whole temperature region  $\Delta T = M_f - A_f$  taking into account its extension under non-stationer conditions. The heat balance in a one complete transformation cycle during the heating of an actuator with a mass  $m$ , a whole heat radiation surface  $A$ , and the electrical resistance  $R$  by means of the electrical current  $I$ , and the followed convection cooling in the air at the temperature  $T_a$  contains the follows terms:

$$\lambda A(T - T_a) = mc_p(A_f - T) + mT_0\Delta s^{AM}z \quad \text{for the cooling and} \quad (1a)$$

$$I^2 R t = mc_p(T - M_f) - mT_0\Delta s^{MA}(1 - z) \quad \text{for the heating (adiabatic conditions)} \quad (1b)$$

where  $\lambda$  is the convection coefficient,  $T$  is the run temperature of the actuator,  $c_p$  is the specific heat of the SMA,  $T_0$  is the equilibrium temperature of the transformation,  $\Delta s^{AM}$  and  $\Delta s^{MA}$  is the entropy of the forward and reverse transformation correspondingly,  $z = \frac{m_M}{m}$  is the phase fraction of the martensite. The heat transfer equations during the forward and reverse transformations is given by the time derivation of equations 1a and 1b:

$$\lambda A\dot{T} = mc_p\dot{T} + mT_0\Delta s^{AM}\dot{z} \quad \text{for the forward and} \quad (2a)$$

$$I^2 R = mc_p\dot{T} - mT_0\Delta s^{MA}\dot{z} \quad \text{for the reverse transformation.} \quad (2b)$$

It can be seen that the follows conditions for the transformation rate  $dz/dt$  must be fulfilled so that there is no intrinsic limiting of actuation frequency:

$$\dot{z} \geq \frac{mc_p \dot{T} - I^2 R}{mT_0 \Delta S^{MA}} \geq \frac{\dot{T}(\lambda A - mc_p)}{mT_0 \Delta S^{AM}}. \quad (3)$$

The conditions (3) show that it is no increasing of actuation frequency possible by unlimited increasing of the electrical power or the cooling rate  $\dot{T}$  if it there is a limit of transformation rate  $\dot{z}$  or  $\dot{m}_M$ .

### ***Transformation rate limiting***

As show the experimental results, it exists an intrinsic transformation rate limit so that the increasing of the external scanning rate do not leads to proportional increasing of the internal transformation rate, but one to the proportional expansion of the transformation interval because the whole process is limited by the smoother process participant, namely, growth of the martensitic phase, which inertia is causes by own transformation heat.

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