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INTERNAL FRICTION MEASUREMENTS AND THERMODYNAMICAL ANALYSIS OF A MARTENSITIC TRANSFORMATION

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Abstract.- Internal friction measurements as a function of temperature and strain amplitude have been performed on polycrystalline CuZnAl and Ti Ni alloys. These measurements show a typical "critical" behaviour round the temperature of the martensitic transformation : discontinuities in the internal friction curves, important decrease of some elastic constants and a thermal hysteresis between heating and cooling.
In order to explain these results, theoretical calculations based on a Landau theory of first order phase transition have been performed. An important strain amplitude dependence is taken into account. It is assumed that the order parameter has the same dynamical behaviour as the one of the dislocations when they break away from pinning points. The thermal hysteresis is then explained without references to the influence of internal stresses.

Introduction.- The experimental features of the internal friction spectrum observed during martensitic transformations have been widely studied in some Fe-based alloys (1), Co Ni (2), Ti Ni (3), Cu Zn Al (4) and so on. In these studies the internal friction has been measured as a function of the temperature for different frequencies (f), different amplitudes of vibration (ε) and different cooling or heating rates ($\dot{T}$). An internal friction maximum has systematically been observed at a temperature corresponding to the temperature of the martensitic transformation. The main features of this internal friction maximum can be listed as follows :

a) The peak height (Q^{-1}_{max}) varies linearly with the heating or cooling rate $\dot{T}$.

b) Even for $\dot{T} = 0$, the maximum is still observed.

c) Q^{-1}_{max} varies linearly with the inverse of the frequency f

d) The internal friction is strongly dependent on the strain amplitude ε for $\varepsilon > 10^{-5}$

The effects of $\dot{T}$ and f on the internal friction spectrum were first described by Belko et al (2) and Delorme et al (1) while the influence of ε was formulated by De Jonghe et al (5). The internal friction during a martensitic transformation may then be written as :

$$Q^{-1} = \alpha \frac{\dot{T}}{f} + Q^{-1}(T,\varepsilon) \qquad (1)$$

In this expression the first term ($\alpha\frac{\dot{T}}{f}$) is only significant in the low frequency range (Hz range). In this paper we will mainly be concerned with the second term and as a consequence, the results presented have been obtained in the kHz range where the first term is very small and then the internal friction depends neither on the frequency nor on the temperature rate $\dot{T}$.

First of all, let us consider the temperature dependence of the internal friction spectrum (6). Figure 1 shows discontinuities in the internal friction and frequency curves as a function of the temperature. These discontinuities lead us to the hypo-

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thesis that the internal friction due to martensitic transformation is a critical phenomenon.

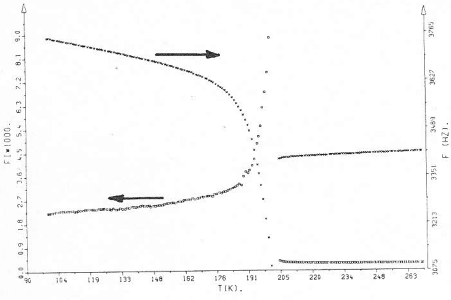
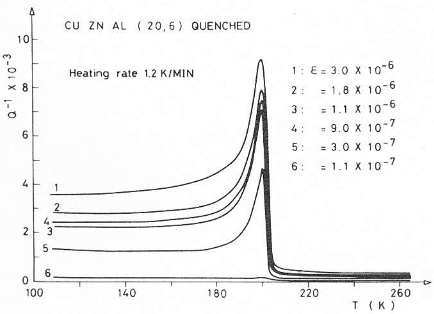


Figure 1 : Internal friction and frequency measured as a function of temperature in a CuZnAl alloy.

In consequence a theoretical calculation of the internal friction, based on a Landau approximation of a first order phase transition (7), will be presented and compared with the experimental results.



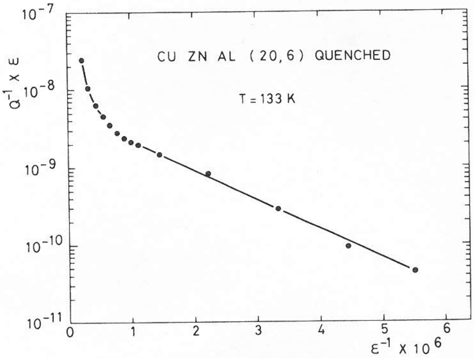


Fig. 2 : Strain amplitude dependence of the internal friction measured during heating in CuZnAl alloy

Fig. 3 : Granato-Lücke plot : $\log \varepsilon \times Q^{-1}$ versus ε^{-1}

Moreover, (Fig.2) shows that for very low value of the amplitude of vibration, the internal friction is strongly amplitude dependent and that this dependence folfollows the Granato-Lücke theory (8) of dislocation breakaway (4)(Fig.3). In order to take account of these results, the relaxation hypothesis used in the first calculation will be replaced by an hysteretical approximation similar to the one used in the case of dislocation damping.

Internal friction during first order phase transition.

The underlying idea behind such a thermodynamic approach is that a pseudo equilibrium can be established within the solid. Assuming that the temperature T is constant, the Gibbs function g may be expanded as a Taylor series in the variables σ (stress) and ξ (internal variable or order parameter). For a first order phase transition Landau proposes (7)

$$g(\sigma,\xi,T) = g(0,0,T) - \tfrac{1}{2} J_u\sigma^2 - \kappa\sigma\xi + \tfrac{1}{2}\beta\xi^2 + \tfrac{1}{4}\gamma\xi^4 + \frac{1}{6} K\xi^6 \qquad (2)$$

where J_u is the unrelaxed compliance and with $\gamma < 0$, $K > 0$ and $\beta = a\,(T-T_c)$

The equilibrium value of ξ is given by $A = 0$, where $A = -\left.\dfrac{\partial g}{\partial \xi}\right|_{\sigma,T}$ is the affinity.

It follows that three different temperatures should be considered (6, 10) : T_c, $T_{eq} = T_c + \frac{3}{16}\frac{\gamma^2}{Ka}$ and $T_h = T_c + \frac{1}{4}\frac{\gamma^2}{Ka}$ with $T_c < T_{eq} < T_h$

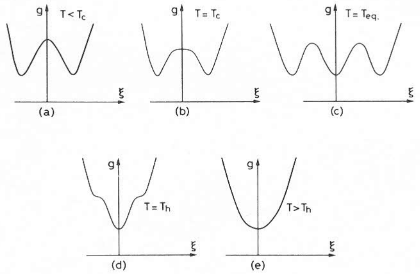


Fig. 4 : Gibbs function g for different values of the temperature (a) $T < T_c$; (b) $T = T_c$; (c) $T = T_{eq}$ (d) $T = T_h$ (e) $T > T_h$

Figure 4 shows the shape of the g function for different values of the temperature. The equilibrium temperature T_{eq} corresponds to the case where the g function (Fig. 4c) has two minima with the same depth. The temperature T_c corresponds to the condition where the central minimum (fig. 4b) disappears during cooling and could be considered as the limit of metastability of the high temperature phase. On the contrary T_h corresponds to the condition where the lateral minimum (Fig. 4d) disappears during heating and could be considered as the limit of metastability of the low temperature phase.

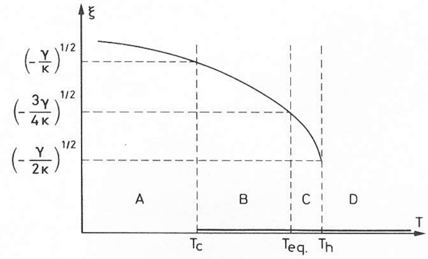


Fig. 5 : Schematic representation of ξ (σ=0) as a function of the temperature. See also ref.(10)

Figure 5 shows the possible value of ξ in the stable or metastable state. According to this figure the phase transition occurs either at T_{eq} without thermal hysteresis or at $T > T_{eq}$ during heating and $T < T_{eq}$ during cooling and in this case a thermal hysteresis is observed. The internal friction will be calculated on the two branches that are for $T < T_h$ in the low temperature phase and for $T > T_c$ in the high temperature phase.

From the Eq. (2) the internal friction is calculated using additionally the relaxation hypothesis

$$\dot{\xi} = MA \qquad (3)$$

and it has been shown (6) that

$$Q^{-1} = \frac{\kappa^2}{J_u}\frac{\omega M}{\omega^2 + \frac{4M^2\gamma^2}{K}\,a\,(T_h - T)\left\{1 + \left[\frac{4Ka}{\gamma^2}(T_h - T)\right]^{\frac{1}{2}}\right\}^2} \qquad \text{for } T < T_h \quad (4)$$

$$Q^{-1} = \frac{\kappa^2}{J_u}\frac{\omega M}{\omega^2 + M^2a^2(T - T_c)^2} \qquad \text{for } T > T_c$$

These results are ploted on fig. 6. The second derivative of g with regard to ξ may be interpreted as an elastic constant, the frequency being proportional to the square root of this constant (Fig. 6b).

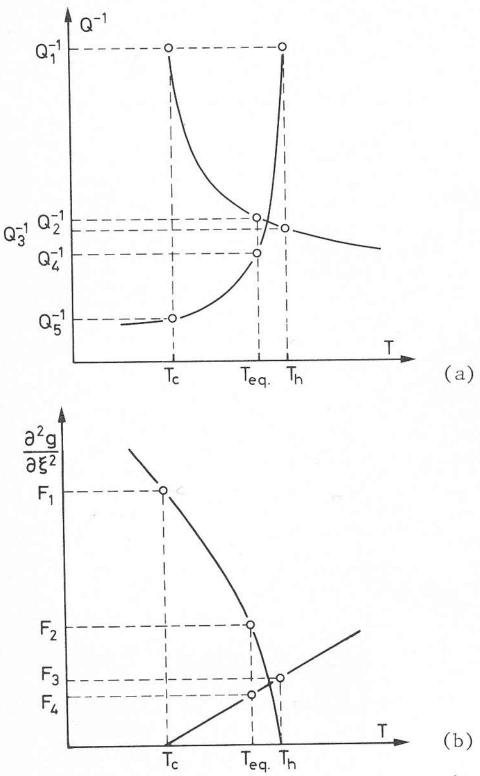


Fig. 6 : Internal friction (a) and $\frac{\partial^2 g}{\partial \xi^2}$ (b) as a function of the temperature.

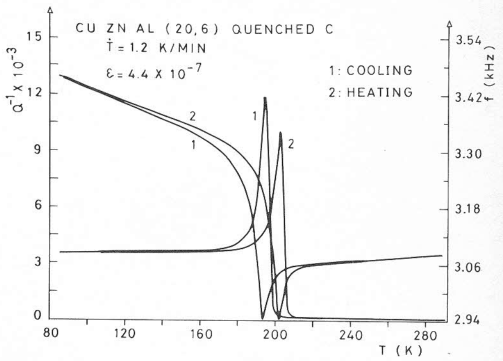


Fig. 7 : Q^{-1} and f as a function of T during martensitic transformation in a CuZnAl alloy (ε=4,4·10^{-7})
Curve 1 : Cooling
Curve 2 : Heating

According to Fig. 6a the internal friction should show a small discontinuity at T=T_{eq} when the discontinuities are much more important at T_h or T_c. Moreover Fig. 6 shows that the critical behaviour ($\frac{\partial^2 g}{\partial \xi^2}$ goes through zero) occurs only at $T = T_c$ on cooling and $T = T_h$ on heating.

So Fig. 1 and Fig. 6 are very similar if it is assumed that the transition occurs at $T = T_h$ during heating. In consequence the thermal hysteresis observed between heating and cooling could be explained (Fig. 7).

In short, the calculation presented gives a very good description of the temperature dependence of either the damping or the frequency observed during heating. It is then obvious that the martensitic transformation could occur at T_h during heating and T_c during cooling. Although an elastic softening mode is observed on cooling, the internal friction spectrum does not verify exactly the theoretical predictions. This fact could be correlated with the introduction of internal stresses during martensitic transformation effect, which has to be taken into account in the expression of the g function.

Frequency and strain amplitude dependence

A systematic study of the strain amplitude dependence of the internal friction spectrum, carried out in a wide amplitude and frequency range, has pointed out the following results :

a) the damping is frequency independent
b) Even in the low strain amplitude range, the damping depends strongly on the strain (Fig. 2) up to an amplitude where a plateau appears, a new increase of the damping being observed at higher amplitudes. The strain amplitude dependence is schematically represented on Fig. 8 where 3 domains are considered.

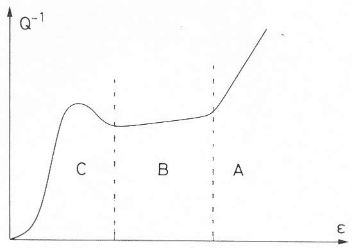


Fig. 8 : Schematic representation of the strain amplitude dependence

The stage *A* corresponds to the case where martensite is induced by the stress and this effect has been described by De Jonghe (4). As already described in the introduction the stage *C* verifies quite well the so called Granato Lücke plot given on Fig. 3. In order to take account of this fact, the calculation summarised previously has to be changed.
More precisely the relaxation hypothesis (Eq. 3) should be replaced by a dynamical behaviour of the order parameter similar to the behaviour of the dislocations when breakaway occurs.
The calculation (6) yields to :

$$Q^{-1} = \frac{C_1}{\varepsilon} \frac{e^{-\frac{C_2}{\varepsilon}}}{\left\{1 + \frac{4M^2\gamma^2}{K} a\,(T_h - T)\left(1 + \left[\frac{4Ka}{\gamma^2}(T_h - T)\right]^{\frac{1}{2}}\right)^2\right\}^2} \quad \text{for } T < T_h$$

$$Q^{-1} = \frac{C_1}{\varepsilon} \frac{e^{-\frac{C_2}{\varepsilon}}}{\left\{1 + M^2 a^2 (T - T_c)^2\right\}^2} \quad \text{for } T > T_c \qquad (5)$$

This equation shows about the same temperature dependence as Eq. (4), but no frequency dependence is considered and the amplitude dependence corresponds exactly to the Granato-Lücke plot of the fig. 3.

Conclusion

The purpose of this paper was to show how the internal friction spectrum measured during martensitic transformation can be explained using thermodynamical analysis. It also shows that internal friction measurements can be used for carrying out information about martensitic transformations. Two types of results have been considered : The internal friction and frequency spectrum measured as a function of the temperature or of the strain amplitude.
Using a Landau phenomonological theory developed in the case of a first order phase transition, important features of the internal friction and frequency spectrum have been explained.
A fundamental point in the application of the Landau theory is the choice of the Gibbs function g and this choice could be the cause of partial agreement between experiments and theory. In any case for the first order phase transition, the critical behaviour does not appear at the equilibrium temperature but at two different temperatures T_c and T_h during cooling and heating respectively.

This result is quite in agreement with our experimental datas.

In the case of a phenomenological Landau theory, the problem of the physical meaning of the so called order parameter ξ still remains. The strain amplitude dependence of the internal friction gives an important information on the dynamical behaviour of this parameter.

In the case of Martensitic transformation the motion equation of ξ around an equilibrium position is not given by a classical relaxation equation ($\dot{\xi} = MA$), but is the same as the one of the dislocations when they break away from pinning points. In consequence our interpretation shows that the martensitic transformation is controlled by a mechanism similar or identical to the motion of dislocations (9).

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