On the origin of acoustic emission during thermoelastic martensitic transformations

Ll. Mañosa[†], D. Rouby[§], J.L. Macqueron[‡], P. Fleischmann[§], M. Morin[§], A. Planes[†].

†: Departament d'Estructura i Constituents de la Matèria. Facultat de Física. Univ. Barcelona (Catalonia).
§: Groupe d'Etudes de Métallurgie Physique et Physique des Materiaux-I.N.S.A. 69621 Villeurbanne (France)
‡: Laboratoire de Traitement du Signal et Ultrasons-I.N.S.A. 69621 Villeurbanne (France)

1.- Introduction

It is well established that intense acoustic emission (A.E.) is generated during martensitic transformations [1,2]. A.E. can be easily detected by suitable piezoelectric transducers. It is usually analysed on counting the number of times that the electric signal furnished by the transducer crosses a prestablished threshold level (ring-down counting technique)[3]. This technique is very sensitive but provides only information at a qualitative level; hence, the physical origin of A.E. signals (A.E. source) cannot be obtained from this kind of measurements. In order to interprete the experimental results in terms of theoretical models describing the A.E. source mechanism, it is necessary to use experimental systems able to digitise the signals at high sampling rates ($>$ 10 MHz)[4].

The aim of this work is to present the possibilities of different A.E. techniques on the study of the martensitic transformations and the main results achieved. The paper is organized as follows: in section 2 we outline the most significant results obtained with the ring-down counting technique, in section 3 we summarize the theoretical background for typical A.E. models and, in section 4, we present some experimental results obtained at high sampling rates and interprete them in terms of an A.E. source model for martensitic transformations.

2.- Ring-down counting

The most common techniques used to analyse the acoustic emission accompanying martensitic transformations are the ring-down counting techniques. The most relevant features associated with them are:

i) The technique is very sensitive, able to detect the transformation of very small amounts of material, even when other techniques (like resistivity, calorimetry,..) are not. For example, the transformation temperature M_s associated to the start of the acoustic activity can be several degrees higher than the M_s obtained with other measurement methods [5,6].

ii) The general A.E. pattern for different alloy systems is dependent to a significant degree on the state of the parent phase, but is reproducible for each specific thermomecanical treatment [7]. Also, in each case, differences in A.E. during forward and reverse transformations have been detected: in most alloy systems the number of counts recorded in the reverse transformation is larger than in the forward one [5,8].

The usefulness of performing simultaneous coupled experiments of A.E. and other physical properties like optical micrography [2,9], electrical resistivity [10] and calorimetry [11] has been stated. In such conditions, a more complete information about the transformation can be achieved.

Article available at http://www.esomat.org or http://dx.doi.org/10.1051/esomat/198906003

Using optical microscopy and A.E., and dealing with a single interface transformation, Baram and Rosen [2] have shown that acoustic activity is only detected when the transformation proceeds in a jerky way. This observation has also been confirmed by other authors [9,12]. The result suggests that the interaction of structural defects with moving interfaces plays a role in the physical origin of acoustic signals.

Other interesting results arise from measuring A.E. simultaneous to thermal emission, using high sensitivity microcalorimeters [11]. Thermal and acoustic records are strongly correlated (see fig. 1)[11,13]. This proves that the physical origin for both effects is the same, and therefore leads to the conclusion that the source mechanism for A.E. is the coordinate motion of atoms during transformation.

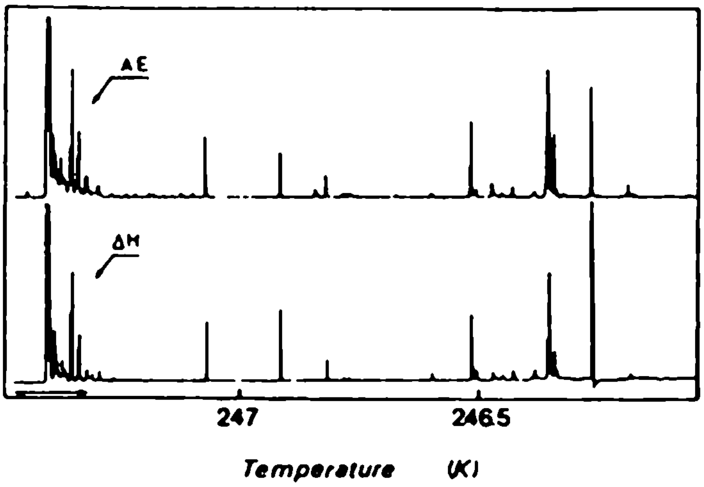

Fig. 1: Records showing the correlation between A.E and thermal power ΔH.

The whole set of results aforementioned provides a basic qualitative information, necessary to define a model for the acoustic emission source in a martensitic transformation. The definitive validity of such model must, however, be checked with experiments specifically designed for such purpose; this will be the scope of sections 3 and 4.

3.- Theoretical considerations

In this section we present useful theoretical background to understand the origin of acoustic waves. It is based on the dynamic Green's function formalism for elastic continuous media [14].

The displacement field created in a solid by an arbitrary displacement discontinuity across an internal surface Σ, can be expressed in a general way as the convolution product:

$$u_i(x,t) = \int_\Sigma \nu_j [u_k] C_{jkpq} * G_{ip,q} \, d\Sigma \qquad (1)$$

where C_{jkpq} are the components of the elastic constants tensor of the medium, $[u_k]$ expresses the discontinuity in the k-direction, ν_j is the j-component of a unit vector normal to Σ and $G_{ip,q}$ is the partial derivative $\partial/\partial\xi_q$ of the dynamic Green function; ξ is a general position on the surface Σ.

Usually, in typical A.E. experiments, only longitudinal waves are detected. In this case, in the far field approximation, and assuming that $[u_k] = n_k \Delta u(\xi,t)$, the following expression is obtained [14]:

$$u_i^L(x,t) = (4\pi\rho|x|c^3)^{-1} C_{jkpq} \gamma_i \gamma_p \gamma_q \nu_k n_j \Omega(t-|x|/c) \qquad (2)$$

where γ_i are the director cosines of the x vector and n_j is the j-component of a unit vector in the direction of the displacement discontinuity. ρ is the mass density of the medium, c the sound velocity for longitudinal waves and $\Omega(t-|x|/c)$ is given by:

$$\Omega(t-|x|/c) = \int_{\Sigma} \Delta\dot{u}(\xi, t-|x|/c)\, d\Sigma \qquad (3)$$

Expression (2) can be analysed adopting two complementary points of view. On the one hand, the kinematics of the process are only contained in the function Ω and, on the other hand, the time independent term determines the radiation pattern, $R_P(x)$, for longitudinal waves, given by:

$$R_P(x) = C_{jkpq}\, \gamma_p \gamma_q \gamma_k n_j \qquad (4)$$

A complete characterization of the source involves the study of both therms.

4.- Results and Discussion.

4.1 Acoustic radiation pattern

To analyse the radiation field $R_P(x)$, we have used a quasi-cubic (5.44x5.46x6.50 mm^3) single crystal (with parallel opposite faces) of a Cu-13.81 Zn - 17.05 Al (at%) alloy, trained in order to activate a single martensite variant when the transformation is thermally induced ($M_s \sim 285K$). From a Laue pattern of the sample we determine the orientation of the crystal faces and of the martensite variant: the three planes are parallel to the (111), ($\bar{1}$02) and (2$\bar{3}$1) planes, and the activated variant is the (011) < 0$\bar{1}$1 > one.

Taking into account these orientations, the radiation patterns for shear ($R_P{}^S(x)$) and volume ($R_P{}^V(x)$) mechanisms, corresponding to longitudinal waves become [15]:

$$R_P{}^S(x) = (C_{11} - C_{12})(\gamma_3\gamma_3 - \gamma_2\gamma_2)/2$$

$$R_P{}^V(x) = C_{11}(2\gamma_1\gamma_1 + \gamma_2\gamma_2 + \gamma_3\gamma_3)/2 + \qquad (5)$$

$$+ C_{12}(\gamma_2\gamma_2 + \gamma_3\gamma_3)/2 + 2C_{44}\gamma_2\gamma_3$$

Several of the acoustic signals generated during the transformation have been recorded. Each of them has been simultaneously detected at four different faces of the sample, by means of four piezoelectric transducers. After amplification, the electric signal furnished by the transducers has been recorded using two digitizing oscilloscopes (Tecktronix 2430A), each one with two independent channels. In order to approach the far field approximation, duraluminium waveguides have been placed between sample and transducers.

The model presented before, leads to the following prediction for the signs (sense of the first motion) of the recorded signals on the different faces:

i) when detected on faces (2$\bar{3}$1) and ($\bar{1}$02) signals must present different sign of their amplitude for a shear mechanism, and the same sign for a volume mechanism.

ii) For both mechanisms the sign of the signal must always be the same when the signal is recorded on opposite faces.

iii) No acoustic emission, associated to a shear mechanism should be recorded on faces (111).

Information concerning the magnitude of the signal amplitude cannot be easily compared with experimental data, since it is strongly affected by attenuation effects [16,17].

In our experiments more than 200 signals have been detected in faces parallel to the (2$\bar{3}$1) and ($\bar{1}$02) planes. They have been analysed in terms of the predictions of the model, about the sign of the amplitude. Results indicate that more than 75 % of the signals can be interpreted according to the theoretical predictions. The remaining 25 % can then be reasonably attributed to parasite signals (noise)and to non-controlled signal reflections in the sample. From the interpretable signals, 63 % correspond to a shear mechanism and 37 % to a volume mechanism.

The results seem to indicate that volume and shear mechanisms act separately in time; this is not a definitive conclusion however, since with the present experimental technique only the signals crossing a threshold level are recorded.

It is important to emphasize that if a random generation of signal signs is assumed, only 25 % of signals could be interpreted in terms of the model.

4.2 Kinematics of the A.E. source

The kinematics of an A.E. source are completely described by the source function $\Delta u(\xi,t)$. The waveforms detected at far field alone cannot uniquely determine such function; for this reason a model is necessary in terms of a small number of source parameters that can adequately describe the source function.

A simple model that approaches quite well a martensitic transformation consists on describing the surface Σ by a rectangular fault plane with lenght L and width W. The fault (displacement discontinuity) initiates at one end of the length and propagates along the length with speed v (see fig.2).

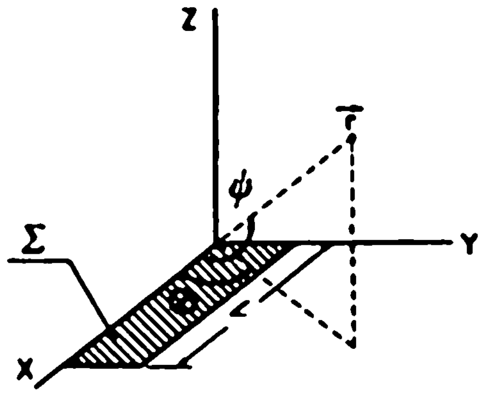

Fig. 2: Unidirectional faulting on a rectangular fault

Assuming W to be small, it can be proved [14] that the fault propagation over a finite length of fault has a smoothing effect on the recorded waveform; i.e. the recorded waveform will present an apparent duration of fault propagation $\tau = L(v^{-1} - c^{-1}\cos\phi)$ for fault speed v, wave propagation c and ϕ the angle formed by the direction to the receiver and the direction of fault propagation.

When analysing the kinetic features of A.E. sources, the waves must be detected in such a way that the experimental set-up itself does not produce any distortion in the recorded waveform. For this reason it is necessary to use broad-band detection systems. In the present experiments, some of the A.E. signals generated during the martensitic transformation have been simultaneously detected on two opposite faces (102) of the sample described in section 4.1. We have used two broad-band piezoelectric transducers; the electric signal furnished by the transducers has been amplified by two broad-band amplifiers and then fed into a digitizing oscilloscope, connected to a microcomputer which is used for off-line processing of the signals. Again duraluminium waveguides have been placed between sample and transducers.

By simultaneous detection of an A.E. signal at opposite faces, the following source parameters can be determined:

i) from the time difference between arrival of the signal at the two transducers (Δt), one can easily obtain the depth of the source (z) as:

$$z = (l - c\,\Delta t)/2 \qquad (6)$$

where l is the total length of the sample, in the measurement direction.

ii) Taking into account that the angle formed by the two directions of detection is 180°, the fault length can be obtained from the difference in the apparent duration of the signals recorded on the two transducers (Doppler effect for A.E. waves):

$$L = (\Delta\tau \cos\psi)/2c \qquad (7)$$

iii) Once L is known, we can obtain the fault speed v from the expression for the apparent duration τ.

In table I we present a few values obtained with the preceding assumptions. These are very preliminar results and, actually, extensive work is in progress, aiming to analyse a high number of signals which can statistically represent the whole transformation.

Table I: A.E. source parameters: depth (z), fault velocity (v) and fault length (L)

z (mm)	v(ms^{-1})	L(mm)
2.41	2292	0.51
0.71	1454	0.26
0.50	582	0.09
2.16	625	0.09

5.- Conclusions

We have characterized, for the first time, the source generating A.E. during the thermoelastic martensitic transformation of a Cu-Zn-Al shape memory alloy. The main conclusions obtained from our study are:

i) It has been statistically proved that two mechanisms are responsible for the A.E. generated during a thermoelastic martensitic transformation: a predominant shear mechanism in the (110) < $1\bar{1}0$ > system and a volume change effect.

ii) We have characterized the kinematics of the transformation by using the Doppler effect. The results presented here show the first experimental evidence of such effect for A.E. waves. We have determined that the transformation proceeds by steps. With the present experimental set-up, we have obtained travelled distances around 10^{-4} m for each transformation step. These values agree well with those measured during optical microscopy observations. The travelling speed has been found to range between 10 to 60 % of the sound velocity for longitudinal waves in these materials.

6.- Acknowledgements

The authors acknowledge the Service Scientifique de l'Ambassade de France in Spain for partial financial support.

7.- References

1.- R. Pascual, M. Ahlers, R. Rapacioli, W. Arneodo, *Scripta metall.* 9 (1975) 79.
2.- J. Baram, M. Rosen, *Acta Metall.* 30 (1982) 655.
3.- C.B. Scruby, *J. Phys. E: Sci. Instrum.* 20 (1987) 946.
4.- C.B. Scruby in *Research Techniques in Nondestructive Testing* Vol. VIII, ed. by R.S. Sharpe. Academic Press, London 1985, p. 141.
5.- J. Baram, M. Rosen, *Philos. Mag. A* 44 (19981) 895.
6.- J.L. Macqueron, Ll. Mañosa, G. Guénin, *Mem. Etud. Sci. Rev. Met.*, Septembre 1987, 494
7.- R. Rapacioli, G. Guénin, J.L. Macqueron in *Proc. International Conference on Martensitic Transformations.* The Japanese Institute of Metals. Nara (Japan) 1986, p. 204.
8.- Ll. Mañosa, A. Planes, E. Cesari, *J. Phys. D: Appl. Phys.* To be published.
9.- A. Amengual, F. Garcias, F. Marco, C. Seguí, V. Torra, *Acta Metall.* 36 (1988) 2329
10.- J.L. Macqueron, M. Robin, in Proc. of "*Jornades de Transformacions Termoelàstiques*". Servei de publicacions de les Illes Balears, Palma de Mallorca (Spain) 1984, p. E.01.
11.- A. Planes, J.L. Macqueron, M. Morin, G. Guénin, *phys. stat. sol. a* 66 (1981) 717.
12.- Ll. Mañosa, C. Picornell, C. Seguí, V. Torra, *J. Acoustic Emission* 5 (1986) S49.
13.- A. Planes, J.L. Macqueron, M. Morin, G. Guénin, L. Delaey, *J. Phys. (Paris)* 43 (1982) C4-615.
14.- K. Aki, P.G. Richards. *Quantitative Seismology*. Freeman, San Francisco (USA) 1980.
15.- Ll. Mañosa, A. Planes, D. Rouby, M. Morin, P. Fleischmann, J.L. Macqueron, *Appl. Phys. Lett.* Submitted.
16.- Z. Yu, P.C. Clapp, *J. Appl. Phys.* 62 (1987) 2212.
17.- Ll. Mañosa, J.L. Macqueron, J.C. Baboux, *Philos. Mag. A.* In press.