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HIGH DAMPING MATERIALS : MECHANISMS AND APPLICATIONS

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Résumé - Les matériaux à fort amortissement sont utilisés largement dans le domaine de la réduction du niveau de bruit et de l'amplitude de vibration dans différentes structures complexes. Cet amortissement élevé peut être structurel ou trouver son origine dans le matériau même. L'amortissement dépend de paramètres externes tels la température, l'amplitude de vibration, la fréquence, le champ magnétique, ... et est déterminé essentiellement par l'état micro-structurel du matériau. On discutera quelques structures pouvant conduire à un amortissement élevé et surtout quelques processus physiques susceptibles de causer un frottement intérieur élevé dans des matériaux tels que les composites, les polycristaux, les hauts polymères ou les amorphes. De tels processus physiques sont basés sur la restructuration micro- ou macromoléculaire dans les matériaux, résultant de la présence de dislocations ou de divers types d'interfaces (parois de domaines, joints de grains, macles, etc.).

Abstract - High damping materials find numerous uses in the field of vibration and noise reduction in more or less complex structures. The high damping required in such structures can be structural damping or materials damping, although the distinction is not always clear-cut. Damping depends on a number of external parameters such as temperature, vibration amplitude, frequency, magnetic field etc. The material microstructure determines largely the mechanism(s) responsible for the damping level in a certain field of external parameter values. A number of possible processes for structural damping will be discussed as well as some of the physical mechanisms responsible for materials damping in composite materials, polycrystalline materials, polymers, amorphous materials, etc. These mechanisms are based on micro- or macromolecular restructuration within the materials as caused by effects of dislocations and various types of interfaces (e.g. domain, twin, interphase or grain boundaries).

1 - INTRODUCTION

The ability of rapidly damping out mechanical vibrations has long been recognized as a very useful material's property, although musicians may not fully agree with this qualification. The study of the mechanical damping properties of solids covers a wide range both of materials and of phenomena. From amorphous elastomers to the most perfect single crystals, all types of solids offer their own specific challenge to the understanding of their internal friction characteristics in terms of dissipation phenomena related either to the behaviour under mechanical stress of individual atoms or to cooperative motions of more or less extended agglomerates of atoms or molecules. Internal friction studies have thus primarily been used to enhance our fundamental knowledge of the mechanical properties of solid materials. Examples of this can be found in the field of phonon-phonon or electron-phonon interaction processes, in the characterization of point defects in crystalline materials (both their symmetry and their migration properties), in the study of dislocations, of grain boundaries or domain boundaries, of glass transitions in amorphous solids, etc.

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(1-4). The use of materials specifically for their damping properties on the other hand appears to be much less documented, although there exist quite a number of applications for both low damping materials (mechanical filters, oscillators, delay lines ...) and high damping materials (noise and vibration absorbers, ...).

In the present review, attention will be focused on high damping materials. Some typical examples will be described of applications where in the design phase of equipment the high level of the damping of the material plays an essential role. Of course, here too the relevant material properties depend on a number of utilization parameters, and a successful design can only be obtained when all of those parameters have been carefully and knowingly taken account of. Clearly this can only be done by due consideration of the mechanisms responsible for the damping behaviour in the material to be used. The largest part of this review will therefore deal with a discussion of the various phenomena which lead to mechanical damping. In addition to situations in which the mechanical configuration of the system leads to a reduction in vibration amplitudes, one will be mostly concerned with structural damping as occurs in composite materials and with materials damping as found in materials that appear more homogeneous on a microscopic (though not atomic) scale.

In order to set the scene for the present discussion, a quantification of the level to be understood under the label of "high damping" is desirable. This is clearly a matter of subjective choice, but a consideration of the experimental data available suggests that a lower bound of $Q^{-1} = 10^{-2}$ is not unreasonable. This excludes most, if not all, of the phenomena related with small scale transport processes of atomic scale entities, focusing the attention to mechanisms based on cooperative types of processes.

2 - POSSIBLE USES OF HIGH-DAMPING

Obviously, applications of the damping properties of materials are to be expected in situations where the occurrence of mechanical vibrations has to be reduced below some critical amplitude. The necessity of limiting vibration amplitudes may be an intrinsic requirement for the correct operation of a system; it may also contribute to the useful life of the system or it may simply originate in a wish to improve the physical comfort of the user or to reduce the impact on the environment.

Vibration isolation of course has to be considered in both directions: oscillations induced by the system on the surroundings as well as oscillations generated in the surroundings and transmitted to the system. As a matter of fact, one should also consider cases in which the vibrations induced within the system may interfere with the desired functioning of the equipment. The mathematical analysis of the mechanical behaviour of complex many degrees of freedom systems can be carried out using modal analysis techniques (5,6). As some typical examples one can mention the reduction of the forces transmitted to the hand of a tennisplayer from the vibrations of his racket (5), the equalization of the spraying density of a fertilizer-distributor by reduction of the vibration amplitudes of the sprayer booms (7) and the improvement of drilling quality obtainable by the introduction of a dynamic damper (8).

Noise reduction is another obvious benefit to be obtained by using vibration absorbing materials in installations subjected to or generating mechanical oscillations, such as a motorcar. Finally, the fatigue-life is determined by the alternating strain amplitudes occurring in the material, and this may cause problems in structural materials such as metals or composites as well as in sensitive structures such as e.g. electronic print plates subjected to strong solicitations as in high g circumstances. It is clear then that high damping materials can be expected to contribute to improving the fatigue performance of oscillating mechanical parts.

3 - PARAMETERS INFLUENCING THE DAMPING BEHAVIOUR OF MATERIALS

Before entering into a detailed discussion of physical mechanisms leading to high

damping levels, a survey will be given of the various physical parameters which have to be considered in evaluating the damping properties of materials. Here, one will consider only external parameters as imposed by the utilization conditions; the internal variables will follow quite naturally when discussing the mechanisms responsible for the observed damping. Of course, it is quite conceivable that external variables (e.g. temperature) will also influence the internal parameters.

Among the important external variables, some have a direct relation with the vibrational state: frequency, strain amplitude, number of cycles. For a linear process which does not alter the material microstructure relevant for the material damping, neither the strain amplitude nor the duration of cycling will have an effect on the damping level. In as much as the interest of the present paper lies in high damping phenomena, however, one will frequently have to deal with non-linear processes and hence with amplitude dependent effects. Also, these effects will often induce changes in the internal structure of the material (e.g. changes in dislocation distribution) and consequently in the damping. Whether frequency will have an effect on the internal friction depends also on the mechanism. If the process causing the damping is a thermally activated relaxation process (even if it is widely distributed), frequency will be correlated with temperature, and in this way temperature will have an indirect effect on the material behaviour. Of course, temperature will also have a pronounced effect on the internal state variables responsible for the damping mechanisms, but this will be discussed later.

Other external variables may also alter the material microstructure and will consequently contribute to changes in the damping. As an example one might mention the effects of irradiation, leading to the creation of point defects in crystalline materials or of cross-linking and/or chain-scission in polymers, the effects of thermal shock, resulting in microcracks, the influence of the surrounding atmosphere causing craze formation or various kind of corrosion, etc.

All of these parameters have to be evaluated for their relevance when designing for vibration reduction in a specific situation.

4 - PROCESSES LEADING TO HIGH DAMPING

When considering the various possibilities of reducing the displacement amplitudes of structural elements of a complex system, one may distinguish very roughly between systems damping, structural damping and materials damping. This is only a very schematic classification, however, since it will be obvious that it is not always easy to clearly define the boundaries between these different types of damping.

In a system with several degrees of freedom, combinations of mass and elasticity can be introduced resulting in zero amplitudes for selected degrees of freedom at well specified frequencies, even without damping. This systems approach for vibration reduction can of course be combined with materials damping by considering the elastic and damping properties of the materials used in the system. In this way one is led to the concept of structural damping, in which the response function of a system can be strongly reduced even at resonance frequencies by the incorporation of structurally damping components. This damping may be caused by external friction or interaction with an external field, e.g. as in an electromechanical brake. It is also possible to use a compound structural member in which the required elastic stiffness and damping are generated in two different materials combined in one unit, as e.g. in a metallic plate covered with a highly damping viscoelastic coating. Such structural damping can be described with reasonable accuracy using the rule of mixtures for both the dissipated (ΔW) and the stored (W) amounts of mechanical energy, so that (using subscripts 1 and 2 for the two components of the composite):

$$2\pi Q^{-1} = \frac{\Delta W}{W} = \frac{\Delta W_1 + \Delta W_2}{W_1 + W_2}$$

As shown e.g. in (9), a damping peak may occur in such a composite as a result of

the simultaneous variations of damping and elasticity in one of the components (in the present case an anorganic glass deposited on a metal base). Also, depending on the relative values of the intrinsic material properties, fibre reinforced matrices may exhibit either higher or lower damping properties than the original matrix (10).

Of course, viscoelastic materials such as anorganic glasses or organic polymers are not the only material modifications exhibiting high damping. It is the purpose of this paper to discuss physical mechanisms leading to high values of internal friction in various classes of materials. Composite materials will not be considered in as much as its damping results from friction between the various component materials. Sources of internal damping, inherent to one of the components, will obviously be treated. Of course, it is not always easy to decide whether a material should be regarded as a composite. Whereas no one will have difficulty with a glass fiber reinforced resin, the case for a glass-ceramic, for a partly transformed thermo-elastic martensite, for a eutectic alloy or may be even for a polycrystalline aggregate is much less clear.

A schematic overview of the gradual transition from systems damping over structural damping to materials damping is given in Figure 1.

5 - MECHANISMS OF MATERIALS DAMPING

Internal friction in a material is the result of irreversibilities occurring during alternating stress cycles imposed on it and these irreversibilities originate in the interactions between the structural components of the material. It may be expected then that a high level of damping can occur only when a considerable fraction of the molecules are allowed to perform relatively long-range excursions between their more or less equivalent equilibrium positions. Clearly, phonon-phonon interactions do not fall under this label. For the well-known case of point defect relaxation effects the required excursion distances correspond with a diffusional jump, and the relaxation strength, which is determined by the anisotropy of the strain field related with the point defect, can in favourable cases reach a value of about one per cent, so that a high damping of say 10^{-2} can occur only in materials with a high solubility for point defects. As an example, one can refer to the old as well as recent results obtained for the Snoek effect in bcc metals such as niobium or tantalum (11). Obviously, we will stand a better chance of obtaining high damping levels by considering mechanisms based on cooperative phenomena. Such phenomena range from dislocation processes over various kinds of interphase boundary motions (grain boundaries, twin boundaries, domain boundaries, ...) to phase change effects (glass transition, martensitic transformation, precipitation, ...).

5.1. - Dislocation damping

The literature on dislocation damping effects has been expanding continuously over the past decades (1-4). However, most of this research has concentrated on the lower damping levels. Yet, it is well known that dislocation relaxation effects are characterized by a relaxation strength determined by ΔL^2 . Hence there is no reason why high damping values should not be observed resulting from high dislocation densities, Δ , coupled with sufficiently large free dislocation loop lengths, L . This is demonstrated in Figure 2, showing the Bordoni peak observed in Mo (12). Also the Granato-Lücke type break-away damping can lead to very high damping levels in favourable cases such as in various magnesium alloys (13,14).

5.2. - Interphase boundary damping

The thermodynamic degree of ordering of a solid is determined by the correlations between an atom and its neighbours and is a function of the external field variables (temperature, elastic field, magnetic field, electric field, ...). For fixed external field values, the spatial orientation of the characteristic directions in the ordered state can still take a number of more or less arbitrary values, and a macroscopically homogeneous solid (in terms of chemical composition) will be heterogeneous on a microscopic level. For a crystalline solid which is not a monocrystal, this will

lead to the presence of grain boundaries and/or twin boundaries. Semicrystalline material contains crystallites embedded in an amorphous matrix (or separated by an amorphous layer) - such grain surfaces occur in semicrystalline polymers and in glass ceramics. The crystallographic order can be supplemented by additional ordering processes, characterized by the existence of a spontaneously ordered state described by a state parameter which is different from zero only below a characteristic critical temperature. Frequently the ordered state can assume a limited number of crystallographically equivalent orientations within any crystal, resulting in the creation of domain boundaries. The nature of the ordered state can be either chemical, elastic, electric or magnetic; the material will be described accordingly as e.g. ferroelastic, ferroelectric, antiferromagnetic, etc. Of course, more than one type of order may occur simultaneously: a ferroelastic material may have developed a spontaneous electric polarization; a ferromagnet will also exhibit a spontaneous deformation.

Provided the order parameter couples with an external field, the domain boundaries will attempt to move in accordance with the direction of the applied field. If furthermore this motion occurs in an irreversible manner, so that the relationship between the field and the corresponding state of order is not a single-valued one, energy will be dissipated. In the frame of this review, the field to be considered is a mechanical stress field, the coupling with the spontaneous strain will result in a modulus defect and hysteresis in the stress-strain relation for a periodically varying field will lead to internal friction.

Probably the best documented effect is the damping related with the magnetomechanical interaction phenomena occurring in ferromagnetic materials, for which a detailed description has been available since the first half of this century (see e.g. (15-18)). Figure 3 shows schematically the influence of a number of parameters on the observed magnetomechanical damping effects. Through the magnetostrictive effect, the well-known magnetic hysteresis curve can be transposed into a mechanical hysteresis curve and this allows one to derive an expression for the amplitude dependence of the internal friction in terms of magnetomechanical material constants:

$$Q^{-1} = c^t \alpha \lambda_s^3 E^2 I_s^{-3} \epsilon \quad (\epsilon < \epsilon_C) \quad (1)$$

Here λ_s is the saturation value of the magnetostriction, I_s the saturation value of the magnetization, E is Young's modulus and ϵ the strain amplitude; α describes the shape of the stress-strain curve in analogy with that of the magnetization curve, assuming that the magnetic susceptibility χ can be written as a linear function of the magnetic field H :

$$\chi = \chi_0 + \alpha H \quad (2)$$

The limiting strain amplitude ϵ_C corresponds with the magnetomechanical coercive stress for which no further stress induced domain boundary motion (or domain reorientation) can occur. For larger amplitudes of vibration, the amount of energy dissipated per cycle remains constant and the internal friction will decrease as ϵ^{-2} .

Of course, this assumption about χ (eqn. (2)) implies that eqn. (1) can be no more than a qualitative approximation. Yet, it indicates that the internal friction will depend on the shape and the steepness of the magnetic hysteresis curve and in particular on the value of the coercive field strength and the saturation magnetization; these parameters can be strongly influenced by structural changes such as internal stress fields. The relative weakness implied by the use of eqn. (2) is illustrated in Figure 4, taken from the work of Masumoto et al. (19) on nickel-cobalt alloys, and which also gives an indication of the damping levels obtained in such materials.

Other types of domain boundaries can obviously also be expected to yield internal friction contributions. Unfortunately, these cases are much less well documented by experimental data and in particular a well-detailed theoretical description is still lacking.

The situation is slightly better when one considers grain boundary effects, for which a much larger set of experimental results is available. Since the first experiments of Kê (20), grain boundary internal friction effects have been widely studied and figure practically permanently on the programme of the conferences on internal friction and ultrasonic attenuation (3,4). Grain boundary relaxation parameters are a function of grain size, d , and grain boundary mobility, $\mu_B = v/\tau$ if v is the grain boundary velocity under a shear stress τ . The actual peak height of the grain boundary relaxation effect depends upon the distribution in grain sizes. This is true also for the peak position, since this is determined by the relaxation time, which is proportional with d and μ^{-1} . The grain boundary mobility is thermally activated with an activation enthalpy which, depending on the boundary microstructure, may take values between 50 % and 100 % of that for self-diffusion. Clearly, grain boundary mobility is also strongly influenced by the presence of impurities, and this can lead to the simultaneous occurrence of several grain boundary relaxation peaks. This is illustrated in Figure 5, showing the effect of internal oxidation and reduction on the position of the grain boundary peak in an Al-Mg alloy (21).

Further difficulties in interpreting high temperature damping peaks in crystalline materials in terms of grain boundary mechanisms arise from the fact that apparently similar effects are observed also in single crystalline samples. (See e.g. the discussions in ICIFUAS 7 (3)). This suggests that the basic mechanisms responsible for the damping peaks are similar too. This is not unreasonable if one takes into account that any detailed description of the grain boundary structure leads to the necessity of considering the simultaneous motion of sets of dislocations. Similar sets of simultaneously moving dislocations can also be expected to occur in single crystals subjected to the high temperatures where these damping peaks occur (homologous temperatures of about 1/2).

These relatively elevated peak temperatures also imply that the mere observation of the effect can cause changes in the material microstructure which can suffice to alter the damping spectrum. This is of course not very favourable for a quantitative analysis of the phenomena. In this respect, twin boundary relaxation effects would appear to be more tractable, since they seem to be governed by lower activation enthalpies. However, the twinning microstructure is not very predictable, nor reproducible, and the amount of experimental investigations of internal friction effects associated with twin boundaries remains still rather small. The increasing interest in both metal-hydrogen systems and thermoelastic martensitic phase transformation effects can be expected to lead to an increasing number of investigations on the anelastic behaviour of twin boundaries.

Evidence for the assignment of an internal friction peak in zirconium to a specific type of deformation twin is presented in this conference ((22), see also (23)). Even higher damping values are reported in the work of Melik-Shakhnazarov et al. (24) on anelastic effects in the β phase of niobium hydride. This is illustrated in Figure 6. These authors relate their observations to the presence of twins in the hydride precipitates and present a model (cfr. Figure 7) explaining the mobility of the twin boundaries under a shear stress as being governed by the redistribution of hydrogen atoms, so that the activation enthalpy for the internal friction peak should be nearly equal to that for hydrogen diffusion. They also show that the relaxation strength is a rather steep function of the hydrogen concentration C_H , as a result of both an increase in the twin boundary concentration and an increase in the twinning deformation (both of these quantities are suggested to vary as C_H^2).

An interesting class of materials, also from the point of view of the high damping levels that can be obtained in them, are those martensite phases characterized by a high density of twins or, more generally, martensite variants. The damping related with the phase transformation itself is discussed in §.5.3. The presence of the variant interfaces usually leads to a high damping level in the martensite phase, frequently superimposed with an intense internal friction peak ascribed to boundary relaxation. A striking example of this effect is given in Figure 8, taken from Sugimoto et al. (25) and showing twin boundary damping in an antiferromagnetic manganese-copper alloy with a martensitic fcc \rightarrow fct transformation at about 130°C.

If one allows for interaction between point defects and the various interface boundaries occurring in the martensite phase, the situation becomes even more complex but also less reproducible. The contribution of Van Humbeeck and Delaey at this conference (26) describes two damping peaks in the martensite phase of Cu-Zn-Al alloys, which are interpreted as being caused by the interaction between point defects, retained in the material following quenching from the high temperature beta-phase, and the dislocations which are present within the martensite plates and/or the plate boundaries.

5.3. - Phase change effects

The cooperative molecular motions occurring during a solid-solid phase transformation can couple with external stress fields and thus lead to energy dissipation. On a smaller scale, in a two-phase material consisting of precipitate particles in a matrix, the shape of the precipitates can be changed under the influence of an external stress and since this will not occur instantaneously, internal friction will result. In as much as this reshaping is conditioned by diffusion processes along the particle-matrix interface, it can also be considered as an interphase boundary effect and it will therefore be discussed first.

Diffusional relaxation around incoherent second phase particles has been described theoretically by Mori et al. (27). They show that the reshaping of ellipsoidal particles in the presence of an elastic stress field leads to a specimen behaving as a standard linear solid. The relaxation strength is found to be proportional with the volume fraction of particles and with the shear modulus of the particles. The relaxation time τ on the other hand is proportional with Ta^3/Dh , in which T is the temperature, a the particle size, D the interfacial diffusion coefficient and h the thickness of the diffusion layer. This particle size dependence of the peak temperature has been confirmed experimentally in Al-Si (28) and in Cu-Fe (29) alloys. However, in Al-Ge alloys in which the precipitates are flat rather than spherical, the peak temperature was found to be independent of ageing treatments and hence presumably of the particle size (30).

As mentioned before, martensitic phase transformations have attracted considerable attention lately (see e.g. (31)). In addition to the boundary mobility effects within the martensitic phase described earlier, the phase transformation itself is characterized also by a very pronounced internal friction maximum, usually accompanied by a dip in the elastic modulus. The peak characteristics are found to depend on a number of experimental parameters such as heating (cooling) rate, \dot{T} , frequency, f , and stress amplitude, σ_0 . The energy dissipation can be related to the amount of material transformed and, taking into account the fact that for a thermoelastic martensite the transformation can be induced by temperature changes as well as by a mechanical stress, the following phenomenological expression for the damping can be derived (32):

$$Q^{-1} = C_1 \frac{\partial m}{\partial T} \frac{\dot{T}}{f} + C_2 (\sigma_0, \sigma_c) \frac{\partial m}{\partial \sigma} \quad (3)$$

Here, $m = m(T, \sigma)$ is the amount of material transformed by a change in temperature, T , and/or stress, σ ; $C_2 (\sigma_0, \sigma_c)$ expresses the fact that for $\sigma_0 \geq \sigma_c$, the phase transformation is stress induced.

The thermoelastic character of the martensitic transformation in certain systems is reflected also in the superelasticity of these materials (Figure 9) and leads to shape memory effects as well. Clearly, the shape of the stress-strain curve in the thermoelastic range contains information about the critical stress σ_c and about the energy dissipated per stress cycle. It also indicates that the strong amplitude dependence observed in the transformation range is expected to go through a maximum since the surface of the hysteretic part cannot increase beyond full transformation of the material, whereas the stored elastic energy can. The complete details of the material behaviour depend strongly on the mobility of the interfaces between parent phase and martensite and hence on the thermomechanical history of the specimen, i.e. on the point defect concentration, the dislocation density, the grain boundary

configuration and the state of order. As a result, the transformation temperature and the damping levels are frequently found to vary considerably with ageing time and temperature. A full understanding of these phenomena is still lacking, although it is clearly required not only from a fundamental scientific point of view, but also if one is to use these materials for either their shape-memory or their high damping properties.

In eqn. (3), the first term is important only at relatively low frequencies and in non-isothermal conditions, whereas the second term reduces to zero for non-thermo-elastic martensitic transformations. Yet, the internal friction still exhibits a characteristic pattern in the phase transformation temperature range for $\dot{T} = 0$ and frequencies in the kHz range, with an amplitude dependence very similar to that observed for dislocation break-away. A qualitative description of the damping to be expected during a first order phase transformation has been recently derived by Koshimizu using the Landau approach (33). Using a Gibbs free energy function (g) expanded in even powers of the variables σ (stress) and ξ (order parameter), up to a term in ξ^6 , it is found that the most characteristic aspects of the damping behaviour can be obtained by making further assumptions about the time dependence of the order parameter, ξ , in terms of the affinity ($-\partial g/\partial \xi$) or in terms of a hysteretic catastrophic dynamical behaviour similar to the one in a dislocation break-away process. In this way the variations with temperature of the elastic modulus and of the damping, the temperature hysteresis between heating and cooling runs and the amplitude dependence can be described in a qualitative way very reasonably.

Whereas most of the damping mechanisms discussed so far are to some extent related to the crystallinity of the solid material, amorphous materials have since long been recognized to be amongst the most highly damping ones. In contrast with crystalline matter, the distribution of relaxation times governing the internal friction behaviour in amorphous solids is usually much wider. Furthermore, for the frequently most prominent absorption peak, corresponding with the so-called glass transition, where extensive viscously damped molecular motion becomes possible, the temperature dependence of the relaxation time can usually not be described by an Arrhenius-type of relaxation. Rather, one has to take into account also the temperature dependence of the free volume in these non-crystalline solids. As a result, the relaxation time as a function of temperature is given by an expression of the form (34):

$$\ln \frac{\tau(T)}{\tau(T_{\text{ref}})} = \frac{C_1(T - T_{\text{ref}})}{C_2 + T - T_{\text{ref}}} \quad (4)$$

In this relation, T_{ref} is a suitably chosen reference temperature. If T_{ref} is taken as the glass transition temperature, C_1 and C_2 are found to be fairly universal constants for a large number of amorphous polymers (34). Eqn. (4) shows that the relaxation time decreases steeply with temperature but with a non-constant effective activation enthalpy. Nevertheless, a time-temperature correspondence remains valid here too, and anelastic data obtained at one frequency-temperature can be translated to other values of frequency and/or temperature provided a master curve such as given by eqn. (4) is available.

A typical damping spectrum for an amorphous polymer is shown schematically in Figure 9, together with results obtained on poly-vinylidene fluoride (35) to indicate the similarity as well as the increasing complexity resulting from the coexistence of both amorphous and crystalline fractions. Also shown is the damping spectrum obtained with coal, confirming the macromolecular character of the coal structure (36).

A temperature dependent activation enthalpy as implied in eqn. (4) is also observed in metallic glasses; by using a simple linear temperature dependence for the activation enthalpy, Berry (37) has indicated that it is possible to rationalize an otherwise unrealistic value of 10^{-25} s for the pre-exponential factor τ_0 appearing in the standard Arrhenius relation.

6 - CONCLUSION

In contrast with most of the low damping level phenomena, in the case of the various processes leading to high damping levels the theoretical basis is much less well developed and also the experimental data base is much more skinny. This is surprising, since applications of the damping properties of materials are based precisely on high damping levels. In recent years, however, more and more physical processes have been identified and confirmed experimentally, and it is to be expected that also the theoretical analysis will soon be put on a better footing. In this way, a better understanding of the effect of the various internal and external parameters on the observed damping levels and on their stability can be expected. This will then allow more possibilities for industrial applications of these material properties to be designed properly.

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FIGURES

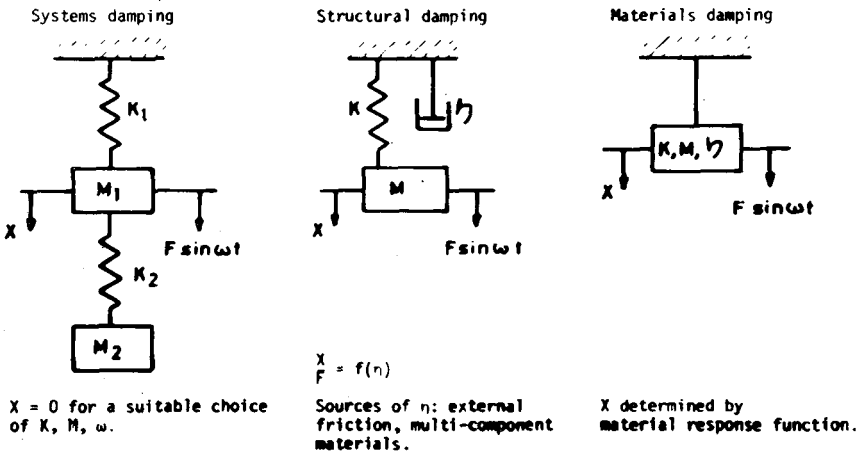


Fig. 1 - Schematic representation of systems damping, structural damping and materials damping.

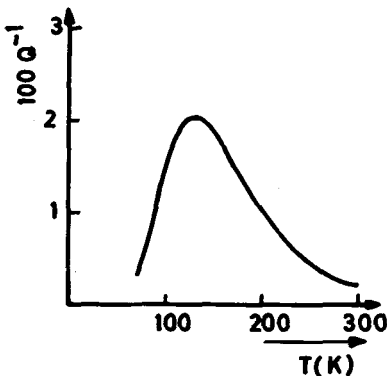


Fig. 2 - The α peak in a Mo single crystal, deformed 3 % at 493 K (12).

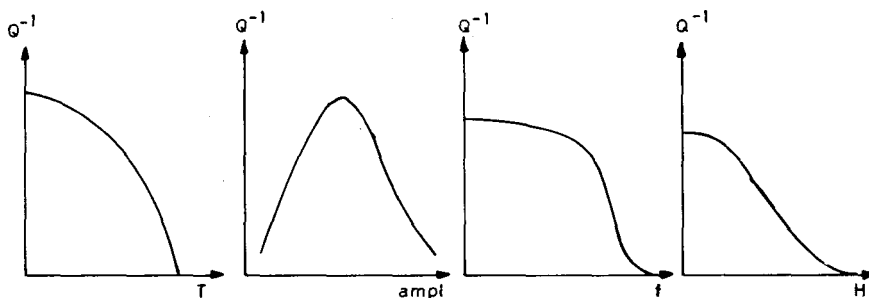


Fig. 3 - Schematic representation of the effect of temperature, amplitude, frequency and field strength on magnetomechanical damping.

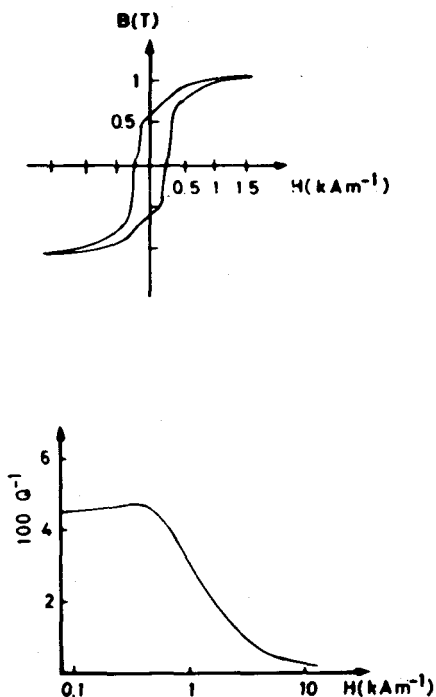


Fig. 4 - Hysteresis loop-shape and field dependence of Q^{-1} , as observed in a Ni-Co alloy (Q_{M}^{-1} is the maximum damping as measured as a function of strain amplitude) (19).

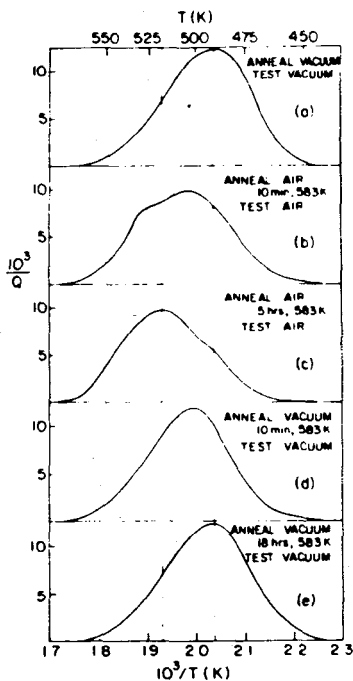


Fig. 5 - Effect of thermal treatment (583 K) and measurement atmosphere on the peak shape and peak position in an Al - 5 % Mg alloy (21).

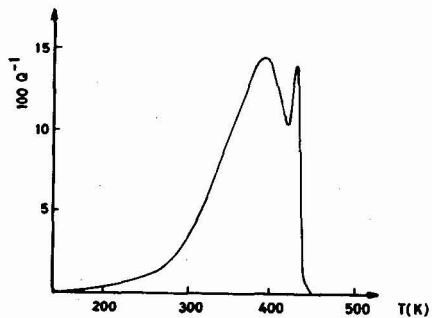


Fig. 6 - Temperature dependence of internal friction in $NbH_{0.94}$ (24).

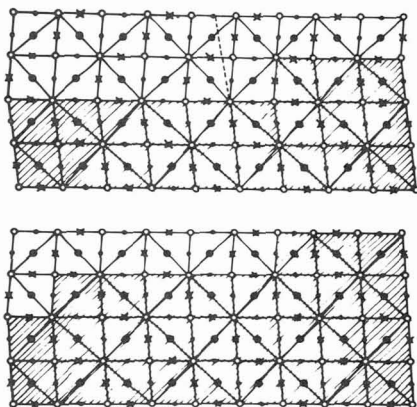


Fig. 7 - Coherent twin boundary in NbH (24).
 $\times, 0$ H atoms at elevation $z = 1/4$,
 $z = 3/4$;
 $\bullet, 0$ Nb atoms at elevation $z = 1/2$,
 $z = 0$.

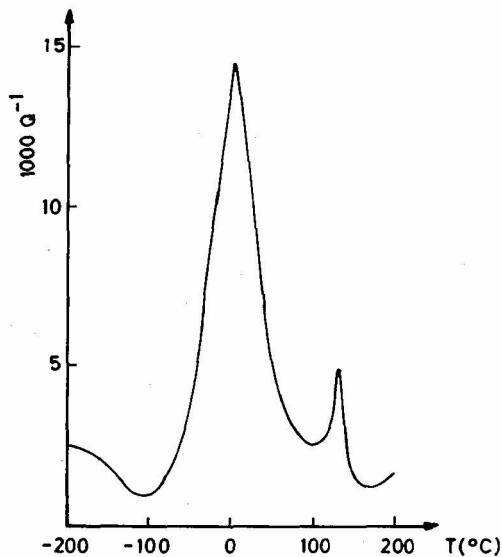


Fig. 8 - Internal friction in Mn - 12 % Cu quenched from 900°C (25).

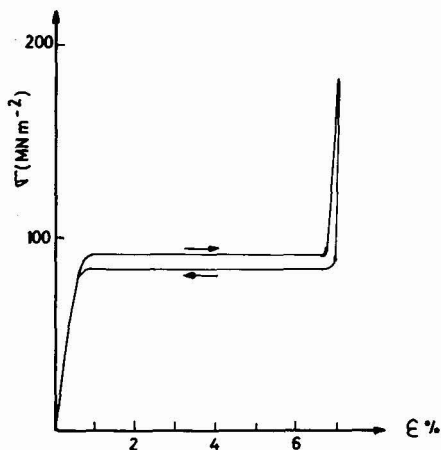


Fig. 9 - Superelasticity in single crystal Cu-Zn-Al (38).

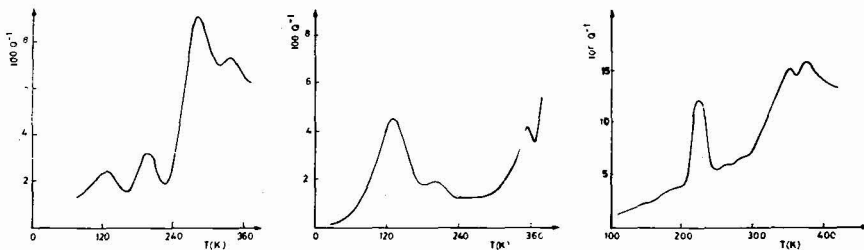


Fig. 10 - Internal friction in (a) amorphous nylon 6 (36), (b) bituminous coal (36) and (c) semicrystalline PVDF (35).