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SNOEK AND ZENER RELAXATION EFFECTS IN METAL HYDRIDES

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Abstract- The main features of anelastic relaxations observed in H(D) loaded pure metals or alloys are reviewed and a discussion is made of results in the literature concerning the H(D) Snoek and Zener effects. As a result of this review it is found that so far the Snoek effect has probably only been detected in pure V and in some Nb and Ti (β form) based alloys. The Zener effect appears to be a common feature of all the non stoichiometric hydrides.

1. Introduction

A fairly large amount of work has been accumulated over the years on the anelastic properties of metal-hydrogen systems. A number of distinctive features have been revealed for H(D) motion and H(D) distortion fields, both in crystalline and in amorphous materials. Most of the acoustical effects have recently been reviewed [1]. Some areas, however, need further discussion, either because new observations have been made, or because conflicting interpretations have been given. These include phenomena associated with stress-induced reorientation of H(D) dipoles (Snoek effect) or with changes of directional short-range-order (SRO) (Zener effect).

2. The Snoek effect

Several investigations have been carried out in the bcc α phase of metal hydrogen systems. In the course of the early researches, internal friction peaks due to H(D) were observed at low temperatures in α -Fe [2], Nb, Ta and V [3,4], and were initially interpreted as Snoek effects. However, more extensive work has laterly shown that the peak occurring in α -Fe is actually a dislocation-related effect [5] and that one occurring in Nb, Ta and V an oxygen

(nitrogen)-H(D) pair reorientation effect [6-8]. Thus further investigations have been undertaken to detect the real H(D)-Snoek relaxation.

The biggest difficulty with this kind of work is related to the fact that at low temperatures, where the Snoek relaxation is expected to occur for the frequencies usually employed in acoustical experiments, the H(D) solubility in the α -phase becomes exceedingly small (few at ppm). For this reason changes induced by (D) in the elastic constants were monitored at high temperatures (usually above RT), where the solubility of H(D) is sufficiently high. Namely the occurrence of a relaxation process affects elastic constants also at temperatures much higher than that of the associated attenuation maximum.

A problem with this kind of approach is that the overall change, ΔC_{ij} , induced by H(D) in the elastic constant C_{ij} results from a variety of contributions such as : a) volume changes; b) anelastic relaxation effects; c) excitation of optic modes; d) changes in the electronic structure of the alloy; e) phase transformations. For the temperatures involved in the experiments dealt with in the present paper the excitation of optic modes is unlikely to occur and the volume as well as the electronic contributions are expected to be temperature independent [9]. Furthermore the phase transformations occurring below RT and of relevance to the present paper are first-order and do not contribute at temperatures higher than the transition temperatures. The total change per unit concentration of H(D) can be thus expressed as

$$\Delta C_{ij} = -C_{ij} S' / [(T - T_1) (1 + \omega^2 \tau^2)] + \Delta C_{ij}^u ; \quad (1)$$

where the non relaxational contribution ΔC_{ij}^u ($\Delta C_{ij}^u = \Delta C_{ij}^{vol} + \Delta C_{ij}^{el}$) is temperature independent; S' is the relaxation constant, T_1 the self-ordering temperature, ω the angular frequency of the applied stress and $\tau(T)$ the relaxation time.

The volume contribution can be calculated by using the following expression

$$\Delta C_{ij}^{vol} = -n\gamma (\Delta V / \Omega) B_T (dC_{ij} / dP)_T ; \quad (2)$$

where n is the H(D) concentration in units of atomic ratio, γ is the Eshelby factor [10] characterizing the volume change in a finite and an infinite sample, B_T is the isothermal bulk modulus ($B_T \equiv B_{adiab.}$), $(dC_{ij} / dP)_T$ the isothermal pressure derivative, ΔV the volume change per H(D) atom and Ω the atomic volume of the host matrix.

In the high temperature limit ($\omega\tau \ll 1$) relation (1) becomes

$$\Delta C_{ij} = -C_{ij} S' / (T - T_1) + \Delta C_{ij}^u \quad (3)$$

For a tetragonal defect in cubic crystals $\Delta C_{44} = \Delta C_{44}^u$, while $\Delta C'$ ($C' = 1/2 (C_{11} - C_{12})$) is given by

$$\Delta C' = -[2nC'_u \Omega / 3 k(T - T_1)] (\lambda_1 - \lambda_2)^2 + \Delta C'_u ; \quad (4)$$

where λ_1 and λ_2 are the diagonal components of the strain field associated with the elastic dipole.

a) Pure metals

Ultrasonic experiments have shown that C' in Nb, Ta and V decreases while C_{44} increases [11,12] with increasing the H(D)-content. The overall decrease $\Delta C'$, has been considered to be relaxational and it has been attributed to the H(D)-Snoek relaxation by Fisher et al. [11], although its temperature dependence was not checked. This check was done in Ta for the shear modulus G by Buchholz [13], who did not observe the Curie-Weiss law of relation (3). Ultrasonic observations on $\Delta C'$ by Magerl et al [12] were also in contrast with (3). Consequently these two groups of authors concluded that H(D) impurities are associated with a cubic distortion field and that the C' softening process was due to causes different from the Snoek relaxation. These conclusions, also reached for the case of Ta by [14], were partly supported by diffuse x-ray scattering experiments, which only revealed a small tetragonality in the strain field of H(D) in V,Nb and Ta [15-18].

More recently Suzuki et al. [19] have obtained for H and D in V and again by x-ray diffuse scattering experiments values for $\lambda_1-\lambda_2$ much higher than those deduced from [18]. Thus a new more accurate ultrasonic investigation has been carried out in V [20], where a H(D) induced decrease of C' has been found to linearly increase with T^{-1} in agreement with relation (3) when T_1 is assumed to vanish (figures 1 and 2). From the slope of straight lines similar to those in figure 2 the quantity $\lambda_1-\lambda_2$ is found to be 0.076 for H and 0.053 for D, in close agreement with x-ray data by Suzuki et al. [19]. These results seem then to support the idea that a Snoek relaxation actually exists in V.

It is to be pointed out that, similarly to what we had previously done for Nb [9], diagrams in figure 2 also give $\Delta C'_U$. Thus for Nb and V we have calculated the shape factor $\lambda_1-\lambda_2$ from the ultrasonic data in the literature after correction for $\Delta C'_U$. The results are reported in table 1. For Ta experimental values of $\Delta C'_U$ are not available, thus the usual volume correction has been applied by using (2) and values for $(\Delta V/\Omega)$ and $(dC'/dP)_T$, taken from [21] and [22]. In this case, apart from data by Fisher et al. [11], $\Delta C'$ turns out to be smaller than $\Delta C'_{vol}$ itself, thus $\Delta C'_{relax}$ has been assumed to be negligible as well as the shape factor $\lambda_1-\lambda_2$.

Inspection of table 1 shows that H(D) interstitials in Nb and Ta are associated with an almost cubic distortion field, as suggested by diffuse x-ray scattering experiments. It can thus be concluded that V-H(D) are probably the only two systems where the Snoek effect has actually been observed.

Table 1 - Shape factor and overall $(\Delta C'/C')$, non relaxational $(\Delta C'/C')_U$, and volume $(\Delta C'/C')_{V0}$, relative elastic constant changes.

System	$(\Delta C'/C')$	$(\Delta C'/C')_U$	$\lambda_1 - \lambda_2$	$(\Delta C'/C')_{V0}$	REF
V-H	20	7.1	0.10	————	Fisher et al.[11]
	20		0.10	————	Ko et al. [54]
	18.3		0.10	————	Magerl et al.[12]
V-D	14.1		0.08	————	Kojma et al.[19]
	10.7	8.9	0.05	————	Kojma et al.[19]
	14.7		0.07	————	Magerl et al.[12]
Nb-H	4.7	4.8	0	————	Magerl et al.[12]
	5.0		0	————	Fisher et al.[11]
Nb-D	3.1	4.8	0	————	Magerl et al.[12]
Ta-H	1.1	—	0	1.8	Magerl et al.[12]
	4.3	—	0.04	" "	Fisher et al.[11]
	1.1	—	0	" "	Stewart III [14]
Ta-D	0.5	—	0	" "	Fisher et al.[11]

b) Niobium -vanadium alloys

Following the observation by Miller and Westlake [23] that Nb-V alloys may have high H(D) solubilities in the α -phase at low temperatures, several investigations have been carried out to detect the internal friction maximum associated with the H(D) Snoek relaxation. Actually a large peak has been reported [24] near 100K (for $f = 0.33$ Hz), whose relaxation parameters are listed in Table 2. As an example results from [25] are reproduced in figure 3 for a Nb-50 at % V alloy. Associated with a well developed peak is a linearly concentration dependent modulus defect.

Table 2 -Relaxation features of an internal friction peak occurring in Nb-V and Ti-V alloys.

System	n (%)	W(eV)	ΔG (1at%)	WIDTH DEBYE	$\lambda_1 - \lambda_2$	REF.
Nb-15at%V	0.29-1.3	0.20	0.034	3-3.5	0.11	Buck et al.[24]
Nb-50at%V	28	0.20	————	3.3	—	Snead et al.[25]
Ti-75at%V	20	0.16	0.019	4.1	0.09	Kato et al.[26]

Regardless of the H content this peak has been interpreted as a Snoek effect, however, this interpretation needs some careful discussion. Let us first confine ourselves to low H contents ($n \leq 0.013$) and to the Nb-15 at %V alloy, which is assumed to be random. Under such conditions the number per unit volume, N_j , of tetrahedral sites having j vanadium atoms as nearest neighbours is given by

$$N_j = B x^j (1-x)^i \quad ; \quad j = 0, 1, \dots, 4 \quad ; \quad i = 4-j \quad (5)$$

where B is a constant and x the mole fraction of vanadium atoms.

As suggested by H solubility data in V and Nb, let us further assume that H(D) atoms preferentially occupy sites with a high number of V atoms as nearest neighbours such as sites N_4 . Thus saturation of N_4 sites would require a H content n equal to 0.0067. For $n=0.0029$ [24] H atoms are distributed through the N_4 available sites and essentially make jumps of type $T_4 \leftrightarrow T_3$. This model implies that the shape factor $\lambda_1 - \lambda_2$ of the dipole at low values of n is substantially the same as that of an H interstitial in pure V. This prediction seems to be confirmed by data in tables 1 and 2.

The activation energy of the relaxation process in this approach is given by the sum of the diffusion energy, which is probably included between, 0.06 eV (V) and 0.11 eV (Nb) and the trapping energy E_T , that is the difference between the energy of sites T_4 and T_3 . E_T is thus found to be in the range 0.09-0.14 eV.

For the Nb-50 at % V alloy, saturation of T_4 sites would occur at $n \approx 0.20$, thus the relaxation features even at the high H contents used in [25] ($0.02 \leq n \leq 0.28$) would be substantially the same as those for the Nb-15 at % V alloy at low H contents, as actually observed (table 2). This is understandable in view of the fact that H-H interactions in these alloys are small compared to the site energies as indicated by the extremely low values of the transition temperatures $T_{\alpha \rightarrow \beta}$ and $T_{\alpha' \rightarrow \beta}$. The absence of strong interactions also accounts for the substantial invariance with changing n of the relaxation features (table 2). On the basis of the picture given here that the relaxation is essentially associated with a single type of jumps ($T_4 \leftrightarrow T_3$) the large relaxation time spectrum is accounted for in terms of the different possible environments of the saddle point configuration as far as occupancy by V or Nb atoms of more distant lattice sites is concerned.

In spite of the fact that the Snoek model outlined above seems to account for the main features of the relaxation, nonetheless, a description of the process based on SRO changes induced by stress (Zener effect), which will be illustrated for other systems in the second part of this paper, cannot be ruled out. Probably the two mechanisms are operative at the same time, the Snoek mechanism being dominant at low and the Zener at high H contents.

c) Titanium - Vanadium alloys

The anelastic response of a Ti-25 at % V in its bcc structural form (β -phase) after charging with H has been investigated by Kato et al. [26] and a high peak has been observed (figure 4), whose main parameters are listed in Table 2. The concentration dependence of the height of the peak shows a maximum value for $n=0.5$.

The peak has again been interpreted as a Snoek effect and the shape factor (Table 2) calculated for $n=0.20$ assuming H interstitials as tetragonal dipoles. Obviously this picture of the phenomenon is meaningless at high H contents unless H-H interactions are proved to be negligible in comparison with the site energies. To our knowledge this information is not available for Ti-V-H alloys, thus, in the absence of such data, we feel that a mechanism based on changes of directional SRO induced by stress seems to be better suited to account for the process at high H contents. Namely, a wide spectrum of relaxation times, as well as a maximum value of S at $n=0.5$ are distinctive features of well understood H-Zener effects [27].

d) Titanium-Manganese alloys

A large peak has also been reported in the bcc β form of $Ti_{1-x} - Mn_x - H_n$ alloys at $x=0.0595$ and 0.0325 and for values of n included between 0.01 and 0.07 . The peak height increases with increasing both x and n and is greater in quenched than in furnace cooled specimens. These features are clearly related to the amount of β phase retained at room temperature, which increases both with the cooling rate and with the concentration of Mn. Thus, as suggested by Someno et al. [28] the existence of a Snoek effect in the bcc form of Ti-Mn alloys at low H content appears to be quite plausible.

3. Zener effect

With the term Zener effect is meant a mechanical relaxation occurring in substitutional alloys, which was initially interpreted as being due to solute pair reorientation [29] and subsequently, more correctly, to changes in the SRO induced by the applied stress [30,31].

According to Welch and Le Claire [31] the relaxation strength, S, is given by

$$S = -n(1-n) \sum_{i=1}^{\infty} \sum_{j=1}^{Z_i/2} [d\alpha_j^i / d\epsilon] (dV_j^i / d\epsilon) / \Omega C^R \quad ; \quad (6)$$

where Ω is the volume of an interstitial site, C^R the relaxed elastic constant corresponding to the deformation mode ϵ . The indexes i and j refer to the shells of neighbours and to the $Z_i/2$ positive directions within the shell, respectively. α_j^i are the Warren-Cowley order parameters given by

$$\begin{aligned} P_{i \text{ H-H}}^j &= n + (1-n)\alpha_j^i \\ P_{i \text{ V-H}}^j &= n(1-\alpha_j^i) \\ P_{i \text{ V-H}}^j &= (1-n)(1-\alpha_j^i) \\ P_{i \text{ V-V}}^j &= 1-n(1-\alpha_j^i) \end{aligned} \quad ; \quad (7)$$

where P_{iV-H}^j means the probability of finding a vacant interstitial site at the position i,j , given there is a H atom at the origin site. V_{ij}^j in (6) is the ordering energy for interstitial site i and direction j :

$$V_{ij}^j = V_{iH-H}^j + V_{iV-V}^j - 2V_{iH-V}^j \quad (8)$$

By assuming central force interactions and making use of the quasi-chemical approach, which only takes into account the ordering parameters α_{ij}^j and the ordering energies V_{ij}^j for first nearest neighbours, relation (6) takes the form

$$S = n(1-n) [n + (1-n)\alpha_{ij}^j] [(1-n) + n\alpha_{ij}^j] (1-\alpha_{ij}^j) (dV_{ij}^j / dr)^2 \sum_{j=1}^{Z_i/2} (dr_{ij} / d\epsilon)^2 ; \quad (9)$$

where α_{ij}^j and V_{ij}^j have also been assumed not to depend on the direction j . The summation term is a purely geometric factor, which has been calculated for C_L , C' and C_{44} modes and for an fcc lattice. Welch and Le Claire have also dealt with this problem in the assumption of more distant nearest-neighbour interactions, but they could not give an analytical expression for S . However, in the high temperature limit an analytical expression for S is obtained

$$S = (n^2(1-n)^2 \sum_{i=1}^{\infty} \sum_{j=1}^{Z_i/2} (dV_{ij}^j / d\epsilon)^2) / \Omega C^R kT . \quad (10)$$

In the case of an fcc lattice the double summation term has been calculated by [32] for C_L , C' and C_{44} modes out to the fifth shell of neighbours. The relaxation strengths are now expressed in terms of the quantities $(dV_{ij}^j / dr_{ij})^2$. Assuming that only first and second nearest-neighbour interactions are important, from the experimental values of S the quantities (dV_{ij}^j / dr_{ij}) and (dV_{ij}^j / dr_2) can be deduced.

In the quasi-chemical approximation and for high temperatures ($2V_{ij}^j \ll kT$) S shows a Curie-Weiss temperature dependence

$$S \propto S' / (T - T_1) ; \quad (11)$$

where T_1 depends on the acoustical mode used.

a) Face centered cubic metals and alloys

The best known example of a Zener effect in fcc metals is probably that occurring within the non stoichiometric α' hydride of the Pd-H system (figure 5). After the pioneering work by Arons [33] the nature of the relaxation was better elucidated by [34] and it is now generally accepted that the internal friction peak is a Zener effect.

The main features of the relaxation are the following :

1) The relaxation strength S displays a Curie-Weiss type of temperature dependence and T_1 coincides with the temperature of the so called "50K transition" [35]; 2) S at first increases ($n \leq 0.64$) then decreases with n as shown in figure 6; 3) the Arrhenius plot of the relaxation time τ_r shows a marked change in the slope around 150 K (figure 7); 4) τ_r is about one order of magnitude smaller than the mean time of stay as deduced from Gorsky effect and NMR; 5) "hydrostatic" relaxation is also found to occur.

The main features of diagrams in figure 6 are consistent with a Zener mechanism operating in the high concentration α' hydride. Namely, according to this picture in a situation of coexistence of α and α' phases ($n < 0.64$), S is expected to be proportional to the volume of the α' phase and consequently to n . For an homogeneous α' specimen ($n \geq 0.64$) S should decrease with n and vanish at $n=1$. All these expectations are in agreement with observations in figure 6.

An important result from the work on single crystals of α' palladium hydride has been the deduction of the interaction forces (dV_i / dr_i) between nearest and next-nearest-neighbours. Such forces are in close coincidence with those deduced for deuterium atoms in a Pd-D 0.63 alloy by neutron scattering experiments. The observation of a relaxation time, τ_r , for the Zener effect one order of magnitude smaller than the jump time, τ_D , deduced from proton NMR or Gorsky effect [36] has stimulated a new theory for proton hopping [37] based on the assumption that strong repulsions among H atoms exist at the saddle point and make hopping to a vacant site unfavorable unless there is another vacant site nearby. This model leads to the conclusion that vacancy motion within vacancy clusters, which is probed by Zener relaxation, is rapid, while motion of an isolated vacancy (probed by NMR) is slow.

From data on the attenuation coefficient measured for C' , C_{44} and C_L modes a relaxation associated with hydrostatic stresses has also been detected thus showing that the H-Zener effect in the α' hydride does not only involve the reorientation of elastic dipoles but also reactions among dipoles, as expected from the model of "directional" SRO assumed by Welch and Le Claire [31] for the Zener effect in concentrated alloys.

Deviations from a single exponential behaviour for the temperature dependence of the H (D) diffusion coefficient in the α' phase of Pd had been inferred by Arons [33] from a composite plot of the relaxation time τ_r and the jump time τ_D (NMR data) against T^{-1} . A deviation was subsequently confirmed and more precisely located along the temperature scale by Gorsky relaxation and permeation data [38]. Results on Zener effect are now available over such an extended temperature range that the non exponential behaviour of the diffusion coefficient can be for the first time reliably determined by means of a unique phenomenon. As seen in figure 7 the transition region included between two separate exponential regimes is situated at

temperatures much higher than previously reported [33]. A similar transition has been observed ($150\text{K} \leq T \leq 250\text{K}$) for the H jump time in Ni [39] and for positive muons in Cu ($200\text{K} \leq T \leq 400\text{K}$) [40]. The two regimes can be accounted for by assuming that over the barrier hopping is the controlling process at $T \geq 200\text{K}$, while tunnelling transitions from the second excited state dominate at $T \leq 120\text{K}$. In this model τ^{-1} is

$$\tau^{-1} = \nu_0 \{ \exp[-W_1/kT] + P_2 \exp[-W_2/kT] \} \quad (12)$$

with P_2 given by :

$$P_2 = \exp(-2/\hbar \int_{x_1}^{x_2} [2m(V(x) - E_2)]^{1/2} dx) \quad (13)$$

The tunnelling transition probability, P depends on $V(x)$. W_2 denotes the energy difference between the second excited state and the ground state

$$W_2 = E_2 - E_0 = 2\hbar\nu_0 \quad (14)$$

From neutron scattering experiments $\hbar\nu_0 = 0.058 \text{ eV}$ [41], thus W_2 turns out to be 0.12 eV , in close coincidence with the value (0.13 eV) obtained from the low temperature part of the diagram in figure 7.

An interesting new observation for Pd deuterides is that a second peak is seen to occur for the longitudinal mode C_L (not for the two shear modes C' and C_{44}) at temperatures lower than the Zener peak [42]. This effect can apparently be associated to stress induced changes of phonon frequencies (Akhieser effect [43]) and consequently to changes of the population of the optical levels by deuterium atoms.

Other examples of the Zener effect in fcc hydrides are those observed in the γ -phase of Zr and Ti by several authors [44-46].

In the $\text{Pd}_{1-x}\text{Ag}_x\text{H}_n(\text{D}_n)$ system the Zener effect was found to split into two distinct peaks for $x \geq 0.40$, as shown for a $\text{Pd}_{53}\text{Ag}_{47}$ sample in figure 8 [47]. In these $\text{Pd/Ag/H}_n(\text{D}_n)$ alloys the limiting solubility in the α phase for a given T , increases with increasing the silver content, x . Thus an interpretation of these peaks was initially given in terms of Zener effects respectively occurring in regions of low (α phase) and high (α' phase) H concentrations. However, the separation into two peaks was found to occur also for values of n so low ($n \leq 0.001$) that only α phase was expected to be present. Furthermore the relative magnitude of the two peaks is affected by the thermal treatments given to the binary Pd/Ag metal alloy before hydrogen charging. All these observations are better understood by assuming that SRO exists within the binary Pd/Ag alloys and that the higher temperature peak $H_{(2)}$ occurs within regions of local silver concentration higher than the average concentration in the specimen. With increasing the H content both

$T_M(H_{(1)})$ and $T_M(H_{(2)})$ decrease, but while $T_M(H_{(1)})$ changes are sensitive to the nominal composition of the binary Pd/Ag alloys those of $T_M(H_{(2)})$ are not. Thus SRO seems to result in domains of well defined composition and in a matrix whose Ag content depends on x.

An anelastic investigation of the Pd/Pt alloys has not revealed any splitting of the Zener effect for Pt contents up to 0.27 [48], thus showing that these alloys are ideal solid solutions.

b) Body centered cubic metals and alloys

A large temperature and H(D) concentration dependent softening of the C' and C_{11} elastic constants is found to occur in Nb, when the $\alpha' \rightarrow \beta$ transition temperature $T_{\alpha' \rightarrow \beta}$ is approached on cooling (figure 9) [9]. Associated with the elastic constant softening is a marked increase in the ultrasonic attenuation. An analysis of the data performed in terms of theories of phase transformations and anelasticity has led to the conclusion that the elastic constant softening and the associated attenuation increases are high temperature manifestations of a Zener relaxation effect occurring at temperatures lower than $T_{\alpha' \rightarrow \beta}$. A fitting to the data of equation 3 provides values for ΔC_{ij}^U , T_1 and S' . The relaxation constant S' is found to pass through a maximum for an atomic ratio H(D)/Nb \cong 0.5. In the high temperature limit the relaxation contribution to ultrasonic attenuation, A, is given by

$$A(d\beta/\mu s) = 4.3410^{-6} \omega^2 \tau S' / (T - T_1); \quad (15)$$

where τ , in the case of strongly interacting particles, can be expressed as [49]:

$$\tau = \tau_0 \exp [W/kT] T / (T - T_1); \quad (16)$$

An analysis of the experimental data in terms of relations (15) and (16) gives values for τ_0 ($\tau_0 = 1.510^{-15}$ s) and W ($W = 0.28$ eV), in agreement with Gorsky measurements and with a phonon dispersion relaxation observed by Magerl et al. [50], for which no explanation had been given before.

c) Face centered ortho-rhombic and hcp hydrides

Ultrasonic investigations of partially ordered non-stoichiometric low temperature phases of Nb $H_{0.78}$ (51), Nb $D_{0.83}$ and Nb $D_{0.86}$ (52) hydrides have revealed two relaxations, which are respectively associated to stress-induced ordering processes occurring within the f.c. ortho-rhombic structures of β and μ (or λ) phases. These peaks show features which can be interpreted in terms of the Zener effect models, as it is discussed elsewhere at this conference [52]. Similarly, an anelastic process occurring in the hcp structure of the α -phase of Lutetium hydride has been interpreted as a H-H pair reorientation Zener effect [53].

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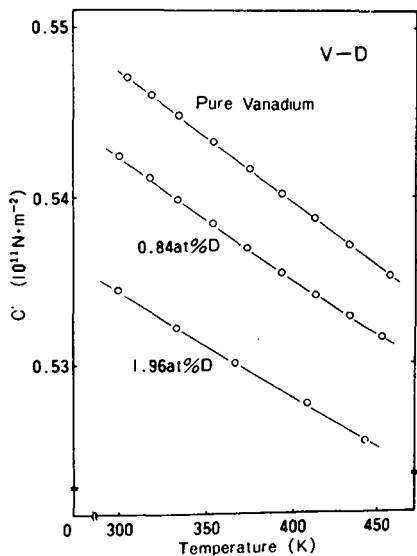


Figure 1: Temperature dependence of the shear elastic constant C for pure V and V - D alloys. From [20].

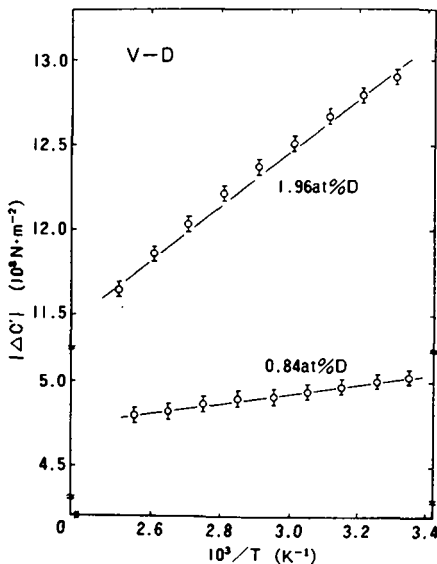


Figure 2: $|\Delta C'|$ of V - D alloys as a function of the inverse of temperature. From [20].

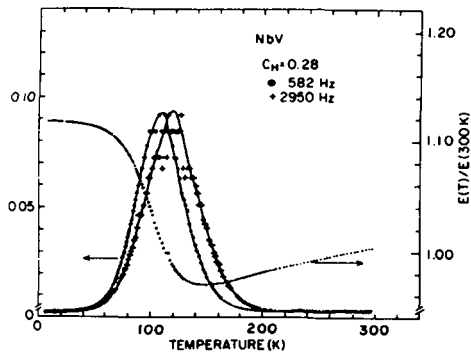


Figure 3: Internal friction and reduced modulus of an H charged ($C_H = 0.28$) Nb - 50 at %V alloy as a function of temperature. From [25].

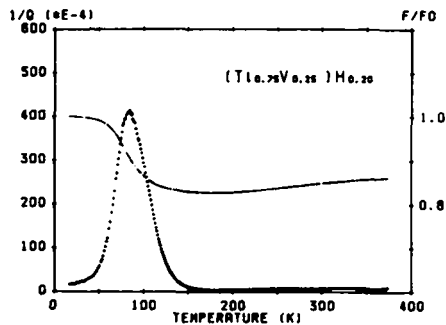


Figure 4: Internal friction and resonant frequency of a Ti - 25 at %V alloy charged with hydrogen to $H/M = 0.20$, measured in torsion. From [26].

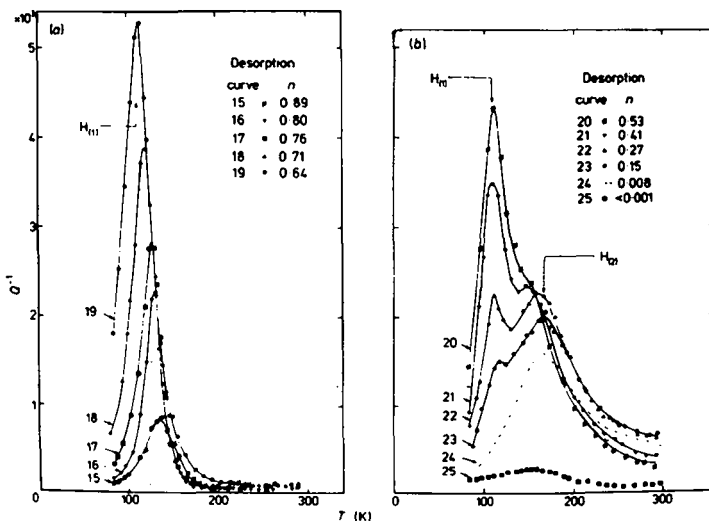


Figure 5: Temperature dependence of the elastic energy dissipation coefficient measured at successively decreased values of the hydrogen content. From [27].

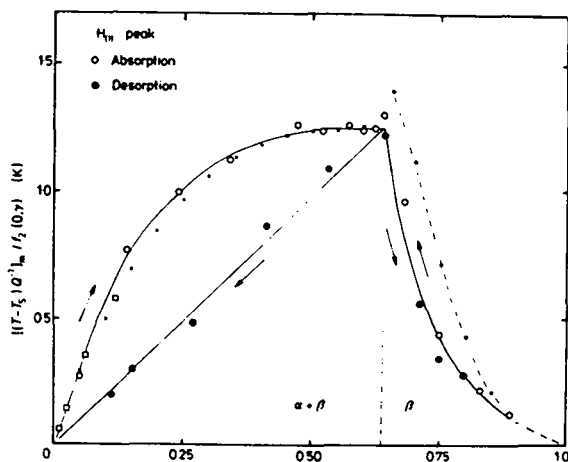


Figure 6: Dependence on the overall H content of the relaxation strength of the Zener effect in Pd. From [27].

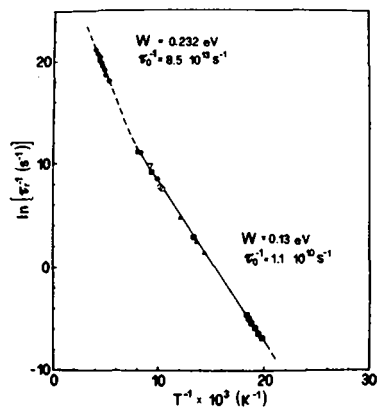


Figure 7: Arrhenius plot for the Zener effect in the α hydride phase of Pd.

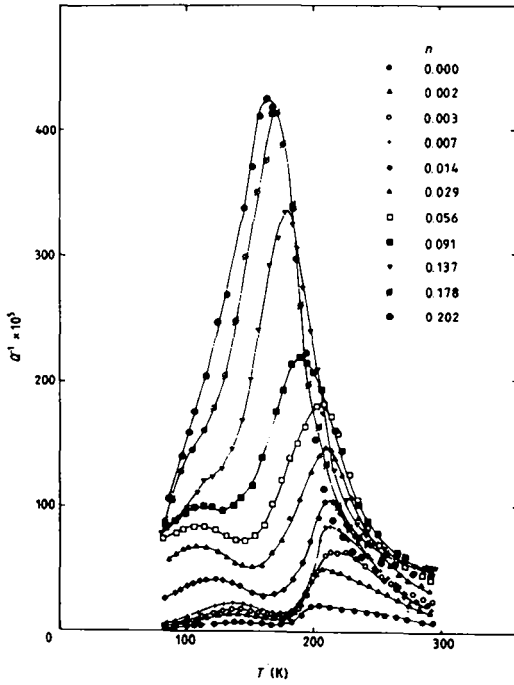


Fig. 8. Internal friction of $\text{Pd}_{53}\text{Ag}_{47}\text{H}_n$ alloy for various H contents.

Fig. 9. Temperature dependence of C_{11}^R for various H/Nb ratios.

