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INTERNAL FRICTION
AND THE STUDY OF RADIATION DAMAGE

THE DEVELOPMENT AND USE OF AN INTERNAL FRICTION TECHNIQUE FOR THE STUDY OF RADIATION DAMAGE

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TITLE: The Development and Use of an Internal Friction Technique For The Study of Radiation Damage

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ABSTRACT

The use of internal friction methods in the study of radiation damage is briefly reviewed. The development of an internal friction technique utilizing a noncontacting optical transducer for detection of flexural resonant vibrations in a cantilever beam is described. An account of some preliminary experiments is given, including examination of the Snoek peak and the strain amplitude dependence of internal friction in iron and niobium. Damping measurements were made in the free-decay mode.

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INTRODUCTION

The interaction of nuclear particles with the solid materials in reactors is one of the major technological problems in the present and projected nuclear industry. Such effects induced by these interactions are the embrittlement of materials and the swelling due to void formation.(1)

A fundamental understanding of the basic physics of irradiation effects is seriously lacking at the present time. As a result, many studies are now being undertaken utilizing different experimental and analytical techniques. This article presents the development and use of one such technique.

I. THEORY

By way of definition, internal friction (I.F.) is the phenomenon whereby the mechanical energy associated with the motion of a material subjected to an oscillatory stress is converted into heat which is irreversibly transferred to the surrounding environment.(2)

This conversion process is the result of anelastic effects within the material. In terms of crystal structure of a solid, anelastic effects are usually due to the displacement of atoms from their normal sites within the lattice. These displacements are termed structural defects. Structural defects created by interaction with nuclear particles are usually of the point defect kind, such as interstitials and vacancies.(3) Hence, the measurement of internal friction in a solid can be used to obtain knowledge about the type and extent of damage within an irradiated solid since I.F. is a measure of the anelasticity of the solid.

Deviation from perfect elastic behaviour (anelasticity) of a solid causes the dissipation of mechanical energy. For a solid undergoing free vibrational motion this dissipation of energy manifests itself in the progressive attenuation of the vibrational amplitude. This effect is called damping. A measure of the damping is the so-called logarithmic decrement:

$$\Delta = \frac{1}{N} \ln\left(\frac{A_o}{A_N}\right) \qquad (1)$$

where N = number of oscillations between A_o and A_N; A_o = amplitude of the first oscillation, and A_N = amplitude of the N'th oscillation. For a perfect elastic material there would be no energy dissipation since under oscillatory conditons, the applied stress and resulting strain are always in phase. Thus, for perfect elastic material Hook's Law would apply.

$$\sigma = Me \tag{2}$$

σ = stress, e = strain, and M = Young's Modulus. However, for a real solid dects give rise to non-elastic effects. Therefore, another mechanical model for a solid is used. This model is the standard linear model of a solid and is depicted as a stress-strain equation:

$$\sigma + \tau_S\dot{\sigma} = M_Re + M_R\tau_T\dot{e} \tag{3}$$

where σ and e are as before, and and e are the first time derivative of these quantities; M_R is the "relaxed elastic modulus", τ_T and τ_S are the ralaxation times for constant stress and constant strain.(4) If the solid is subjected to an oscillatory stress given by:

$$\sigma = \sigma_o \sin(\omega t) \tag{4}$$

then the resulting strain is:

$$e = e_o \sin(\omega t - \Phi) \tag{5}$$

ω is the angular frequency of the oscillations and Φ is the phase lag angle of the strain. Thus, Φ is a measure of internal friction of the solid. Substituting equations (4) to (5) into equation (3) yields a dynamic modulus M such that:

$$M = M_R \frac{1 + \omega^2 \tau_T \tau_s}{1 + \omega^2 \tau_s^2} \qquad (6)$$

also

$$\Phi = \frac{\omega(\tau_T - \tau_s)}{1 + \omega^2 \tau_T \tau_s} \qquad (7)$$

By introducing the geometric averages:

$$M_o = (M_U M_R)^{1/2} \quad \text{and} \quad \tau = (\tau_s \tau_T)^{1/2}$$

we find:

$$\Phi = \frac{M_U - M_R}{M_o} \cdot \frac{\omega\tau}{1 + (\omega t)^2} \qquad (8)$$

This is the well-known Debye relaxation function. The quantity Φ is a measure of the internal friction and when plotted as a function of $\ell n(\omega\tau)$ a maximum is obtained for:

$$\omega\tau = 1 \qquad (9)$$

Different structural defects in a solid exhibit relaxation phenomena usually associated with a characteristic τ. Thus, if either ω or τ is held constant and the other varied a peak in the internal friction Φ will appear $\omega\tau = 1$. In this study, ω is a constant and τ is varied by varying the temperature T.

The relationship between τ and temperature is the classical Arrhenius type:

$$\tau = \tau_o \exp^{(Q/kT)} \tag{10}$$

where Q is the activation energy of the process and k is the Boltzmann constant. This relationship usually holds for relaxation of point defects in solids.

Interstitials and vacancies are the simplest types of defects created within an irradiated sample. Thus, the interstitials and often more complex damage clusters of interstitials and vacancies give rise to relaxation peaks in the IF. spectrum at low temperatures. An example is shown in Fig. 1, which is the result of work done by the Grenoble Group in France.(5,6) This is for neutron irradiated iron between 0 and 300°K. Several peaks are shown which correspond to different types of damage.

In this report, we study impurity interstitial defects. The relaxation peak is the so-called "Snoek" Peak, and is due to carbon and nitrogen interstitials in iron and oxygen in niobium. The "Snoek" peak is fairly well chacacterized and documented in literature; thus, we used this as a test of our experimental I.F. rig.

II. EXPERIMENTAL

The technique used was a modified simple contilever beam, excited to undergo transverse flexural vibrations. The specimen is a "T" shaped sample of pure iron or niobium as shown in Fig. 2(a). The sample is clamped at the top portion of the "T", leaving the bottom portion free to swing about the swinging point as shown in Fig. 2(a). This arrangement was used to minimize the effect of "cold working" introduced by the clamp. Cold working by the clamp was found to be significant when a rectangular cantilever was used since the clamping point was at the point of largest stress in the vibrating specimen. With use of a "T" shape this problem was reduced.

The beam was deflected electrostatically by a capacitive drive system. This was accomplished by placing a drive plate 1 mm from the specimen and applying an alternating voltage between the sample and plate. Since the force was only attractive, the a.c. voltage was applied at half the resonant frequency of the cantilever. For a sample with approximately 1 cm length from the swinging point and 0.1 mm in thickness, the resonant frequency was found to be in the 500 Hz region. This arrangement was used because of several advantages, the major advantages being that: (i) at 500 Hz, the contribution of background mechanical noise, usually from 0 to 100 Hz(2), would be minimal; (ii) the size and shape of the sample make it convenient to use the system in an accelerator based irradiation experiment.

A Fotonic* sensor was used to detect the deflections at the end of the cantilever. The sensor consists of two light pipes (fiber bundles) as shown in Fig. 3. One pipe emits light and the other receives and senses the intensity of the reflected light. The intensity of reflected light has been found to be proportional to the displacement of the reflected surface from the end of the sensor.(7) Output of sensor vs. displacement is plotted in Fig. 4 and a linear region exists at approximately 0.033 in, and was used as the operating region. The frequency response of the device was flat in the kilocycle range.

It has been shown (8, 9) that in order to eliminate contributions to the damping created by the magnetic domain shifting in iron, it is necessary to subject the sample to a saturating magnetic field. This was accomplished by installing a permanent magnet as shown in Fig. 2(b). By moving the magnet probe ends relative to the sample position, the magnetic field applied to the sample could be varied in a controlled manner. This enabled us to study the affect of the field on the iron.

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* Trade name

III. RESULTS

Several strain amplitude vs. damping curves were done for iron samples for different applied magnetic fields. The results are shown in Fig. 7. Also in Fig. 7 is shown similar curves done by Guberman and Beshers(9). The Log Dec. is plotted on the left which was taken from trace of a decay similar to Fig. 6 and calculated using Equation (1) for each strain amplitude. The strain amplitude can be calculated(10) from:

$$e_{max} = 0.63 \text{ X } \frac{aY_o}{\ell} \qquad (11)$$

where a is the thickness, ℓ is the length of the cantilever, and Y_o is the maximum displacement at the end of the sample. The displacement was measured using the Fotonic sensor. The material used was nominally pure iron. Curves 1 and 2 of Fig. 7 were for a specimen in a simple rectangular form. Curve 2 is for an applied magnetic field of approximately 110 Oe and curve 1 for 0 magnetic field. Similar curves for 0 and 110 Oe magnetic fields are shown, 3 and 4; however, it is a "T" shaped sample, annealed at 800°C for two hours. Curves 5 and 6 are taken from the work of Guberman and Beshers(9) and is also for pure iron subjected to 0 and 110 Oe magnetic fields, respectively.

Fig. 8 shows the result of varying the temperature of iron specimen between 20°C, these peaks were thought to correspond to the nitrogen and carbon Snoek peak in iron.

Niobium was also investigated, and the results are shown in Fig. 9. Similarly to iron, a pronounced peak was observed at 230°C and is thought to correspond to the oxygen Snoek peak in niobium.

IV. DISCUSSION

Changes due to the use of a "T" shaped sample as opposed to a simple rectangular shape, can be seen in Fig. 7 from the large difference in the damping between curves 1 and 3. The result of applying a magnetic field is the lowering of the damping of a given iron sample. This is seen in the difference between curves 1, 2, 3, and 4. Curves 3 and 4 of Fig. 7 also agree reasonably with the work done by Guberman and Beshers depicted by curves 5 and 6(9).

Observation of carbon and nitrogen Snoek peaks in iron, and an oxygen Snoek peak in niobium confirms that the damping level was sufficient to see relaxation effects of defects. The shape and peak temperature of the peaks agree well with those given in literature(8, 11).

V. CONCLUSIONS

Internal friction of both iron and niobium in a "T" shaped sample can be measured by our experimental I.F. rig. The background damping was sufficiently low to permit observations of the relaxation Snoek peaks. Thus, it is concluded that the present experimental arrangement will be useful in the detection of relaxation effects due to radiation damage. Mating of the I.F. rig with an irradiation facility will now be undertaken.

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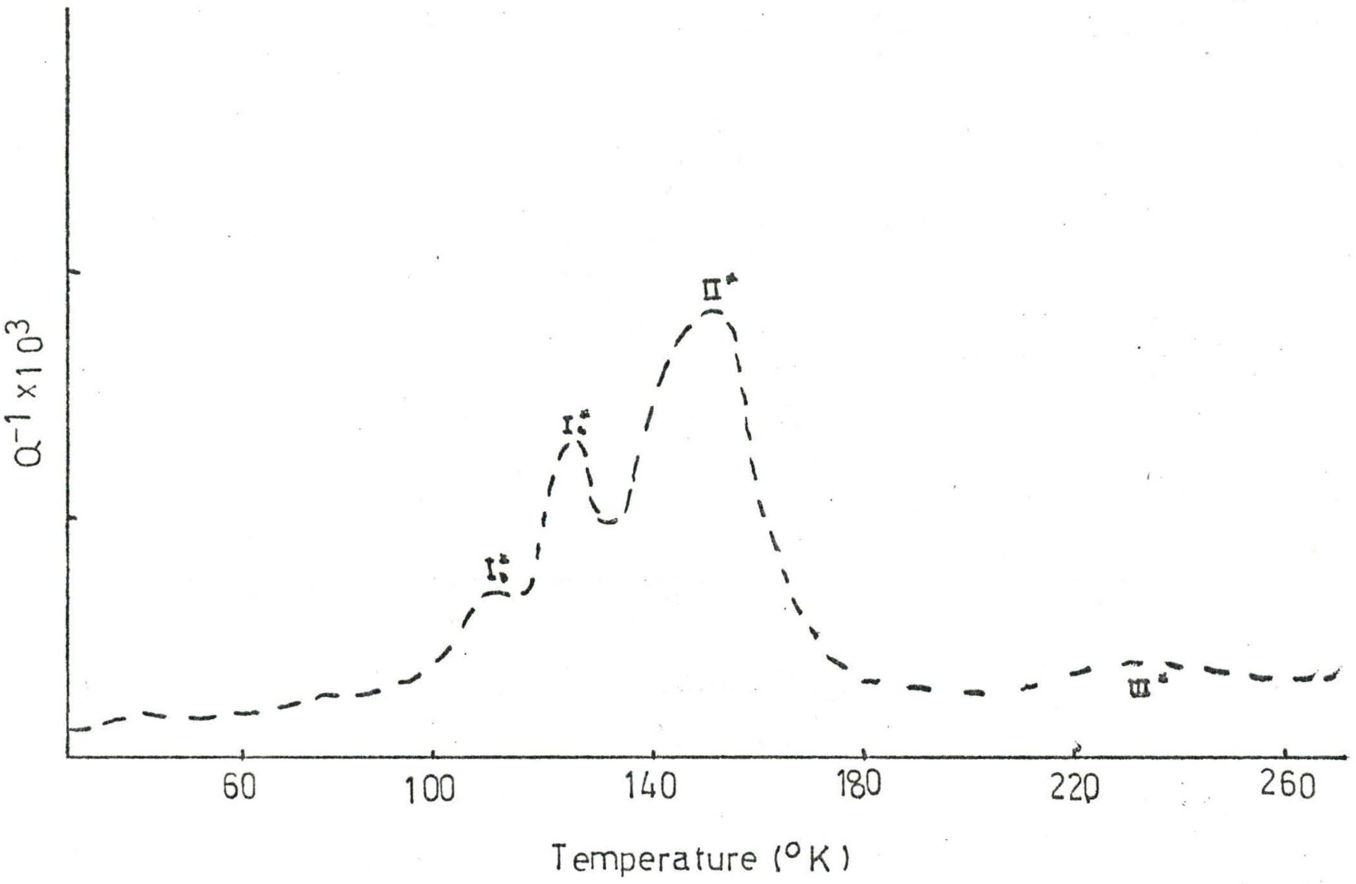

Fig. 1: I.F. Spectrum for neutron irradiated iron taken from work of V. Hivert et. al. (1969).

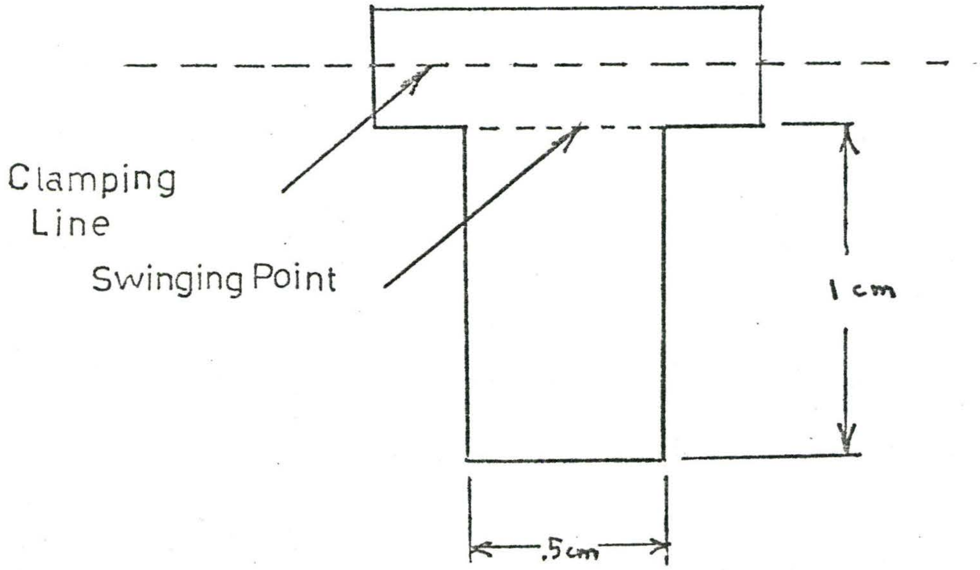

Fig. 2(a): Modified "T" shaped sample.

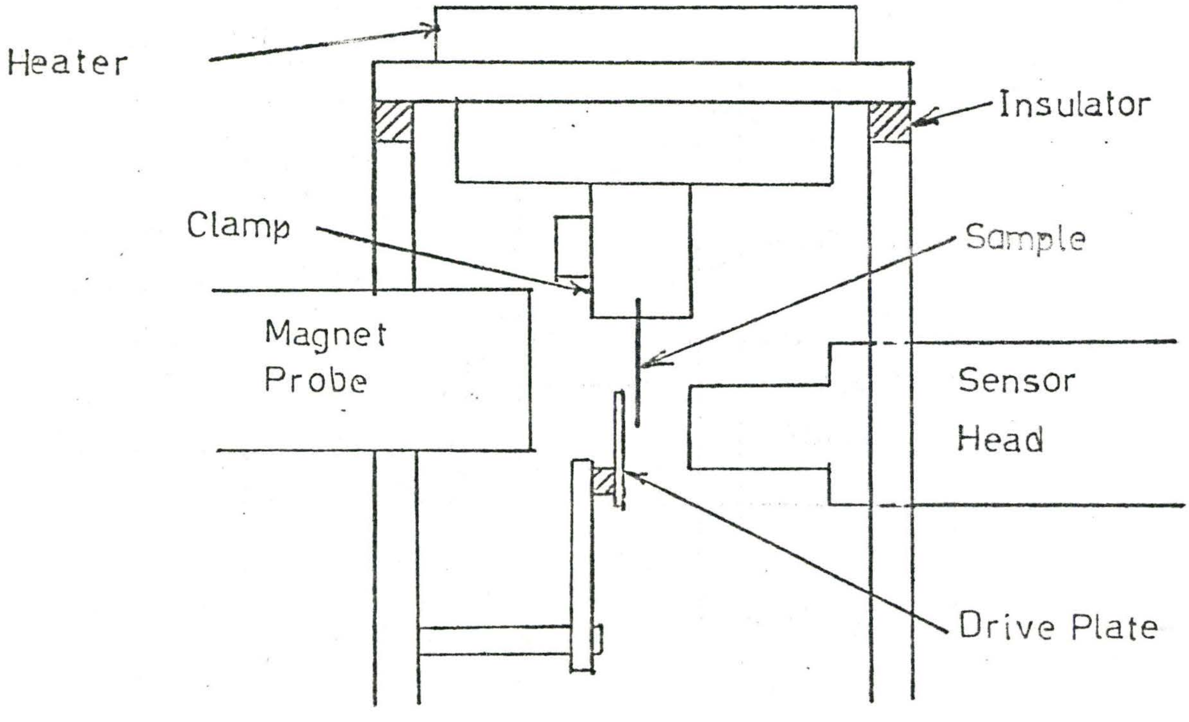

Fig. 2(b): Sample clamping, driving and sensing arrangement.

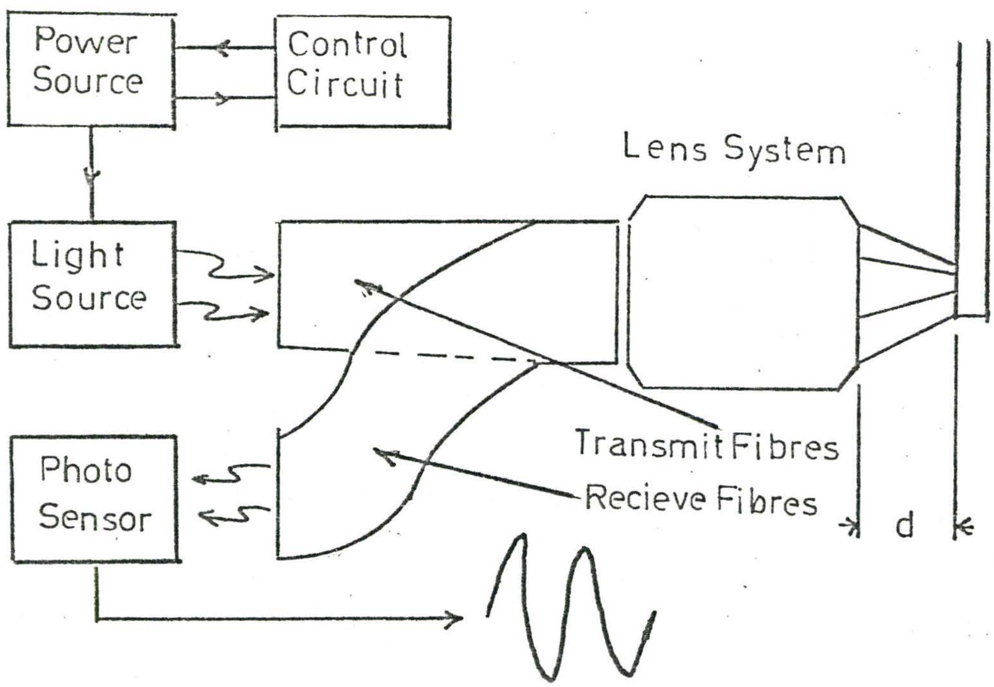

Fig. 3: Optical sensor system.

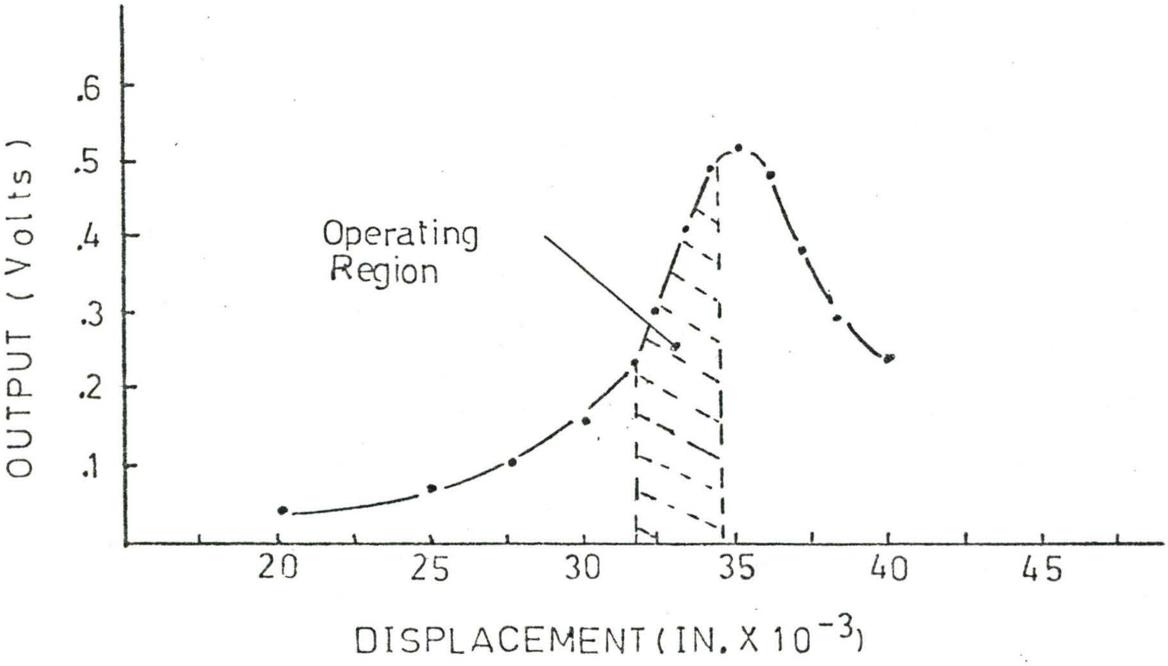

Fig. 4: Plot of output vs. displacement for the optical sensor system.

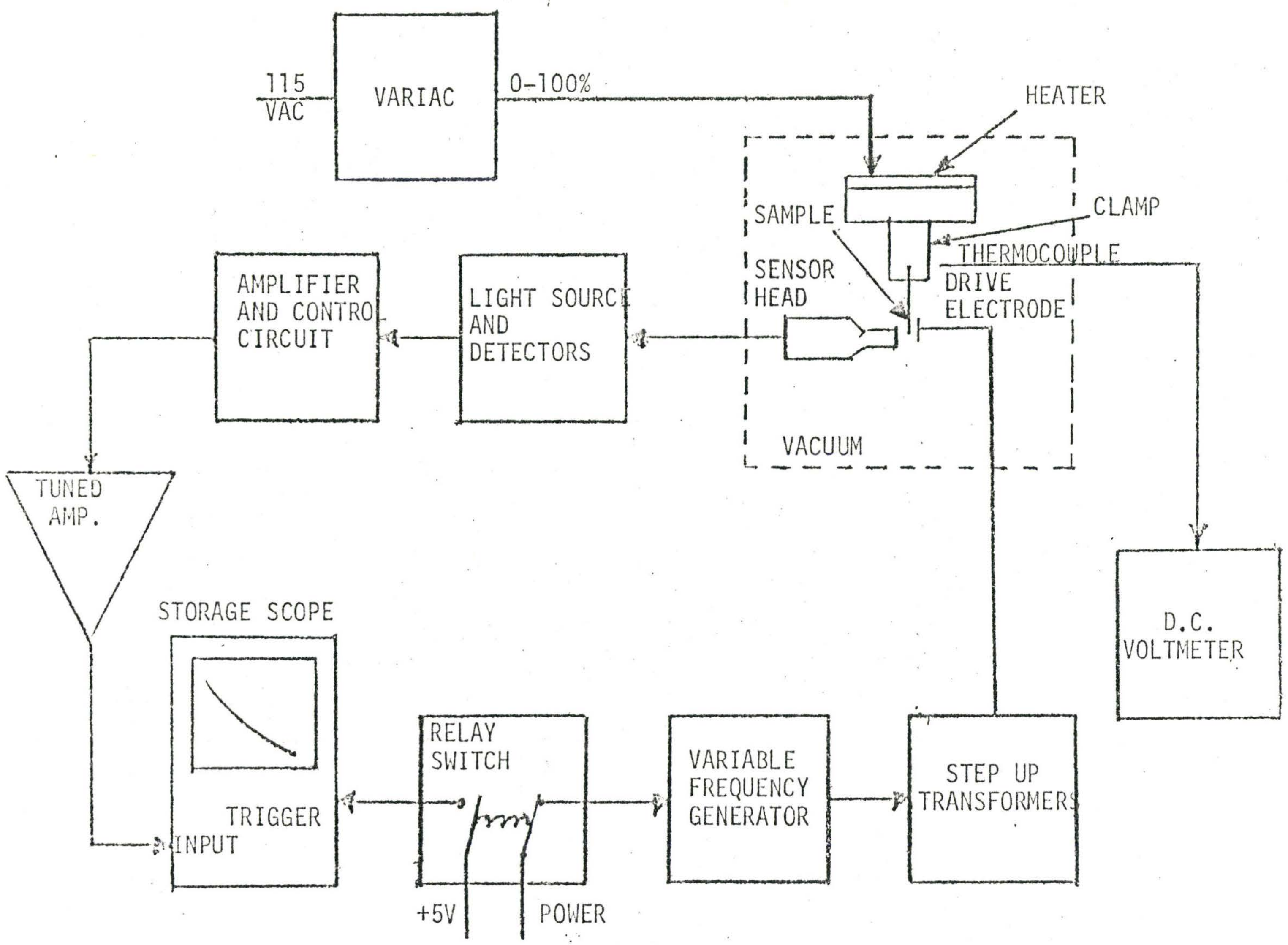

Fig. 5: Schematic diagram of internal friction (IF) system

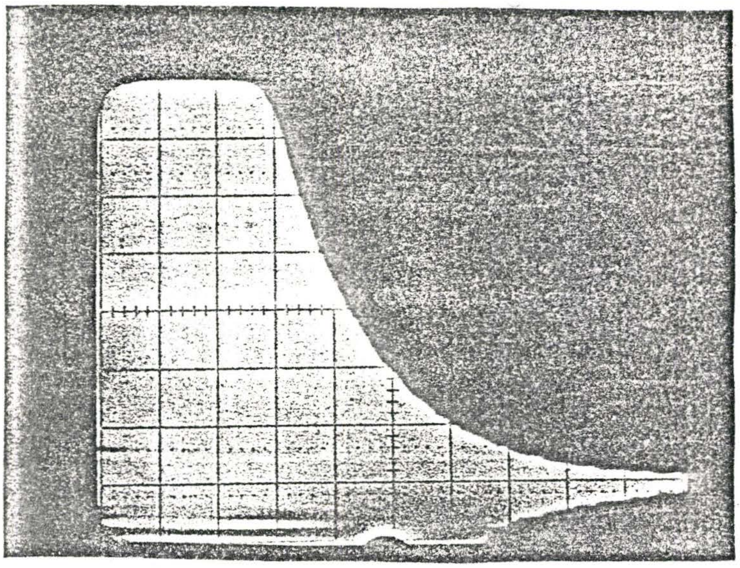

Fig. 6: Photograph of a sample decay trace used in measuring the log. dec.

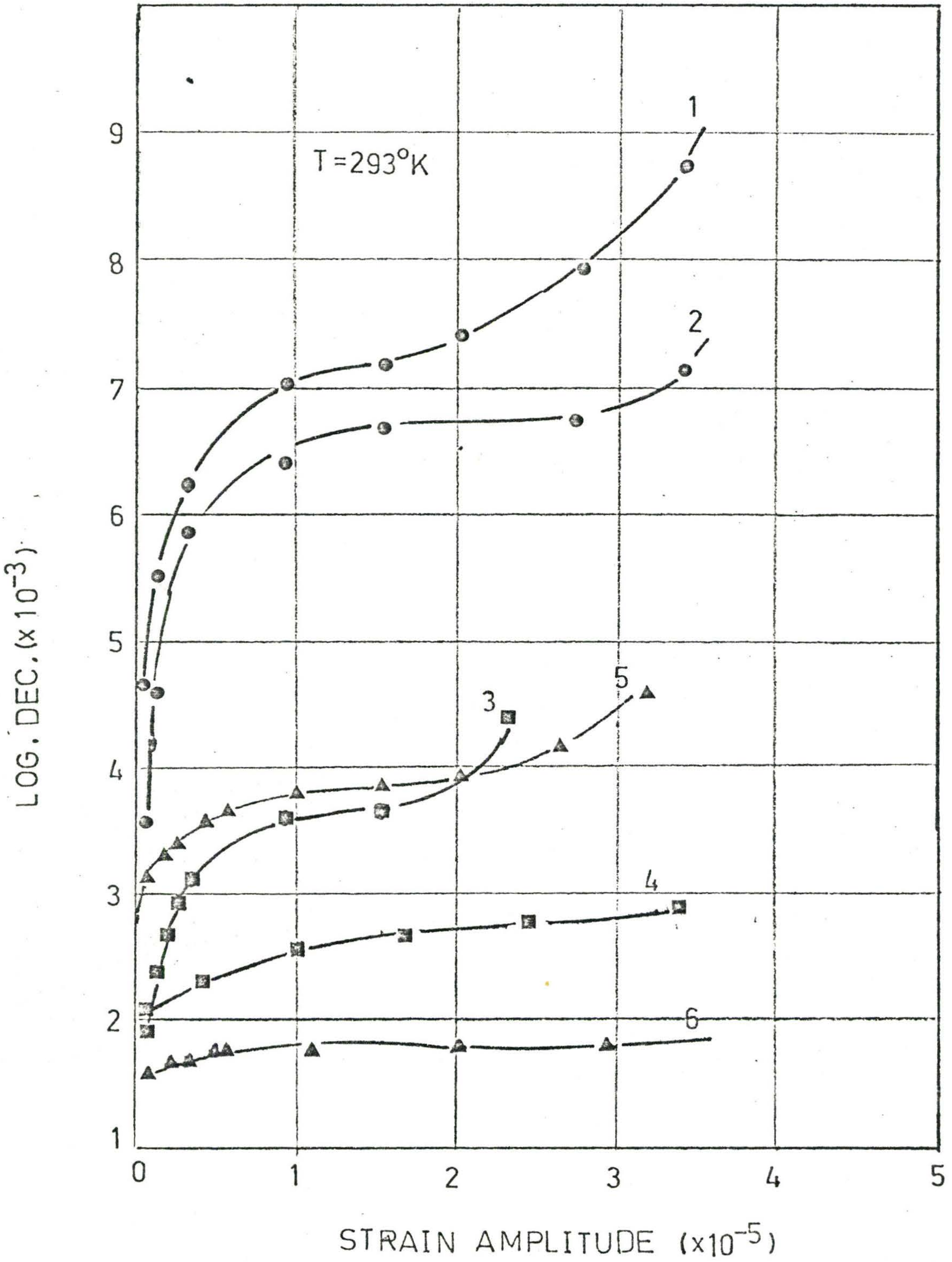

Fig. 7: I.F. vs. strain amplitude as given by Equation (1) and (11). Curves 1, 2 is for a simple rectangular specimen subjected to 0 and 110 Oe magnetic field. Curves 3,4 is for modified "T" shaped sample, with 0 and 110 Oe magnetic field. Curves 5 and 6 are taken from the work of Guberman and Beshers (1968).

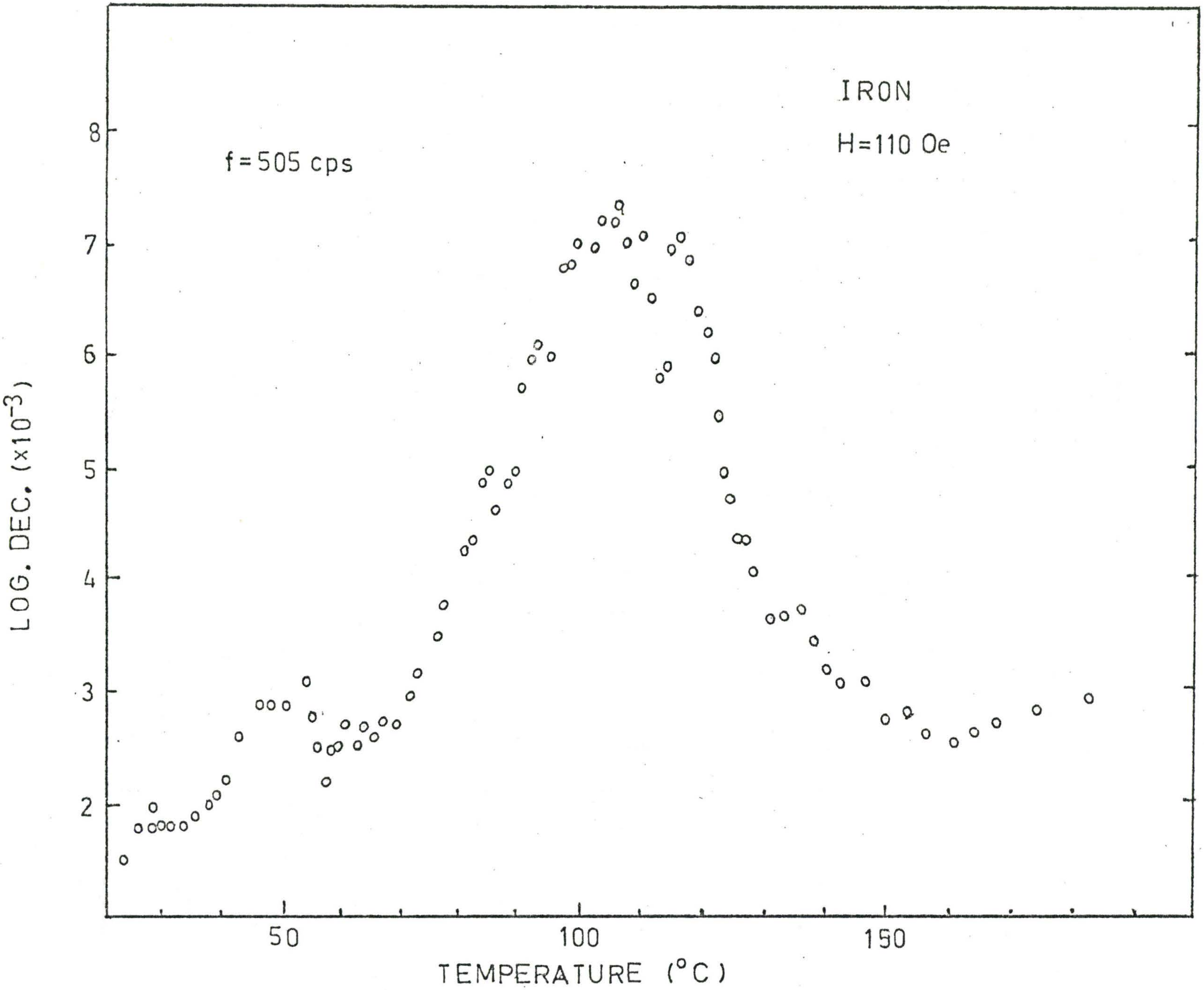

Fig. 8: I.F. spectrum for nominally pure iron in the temperature range of 20° to 200°.

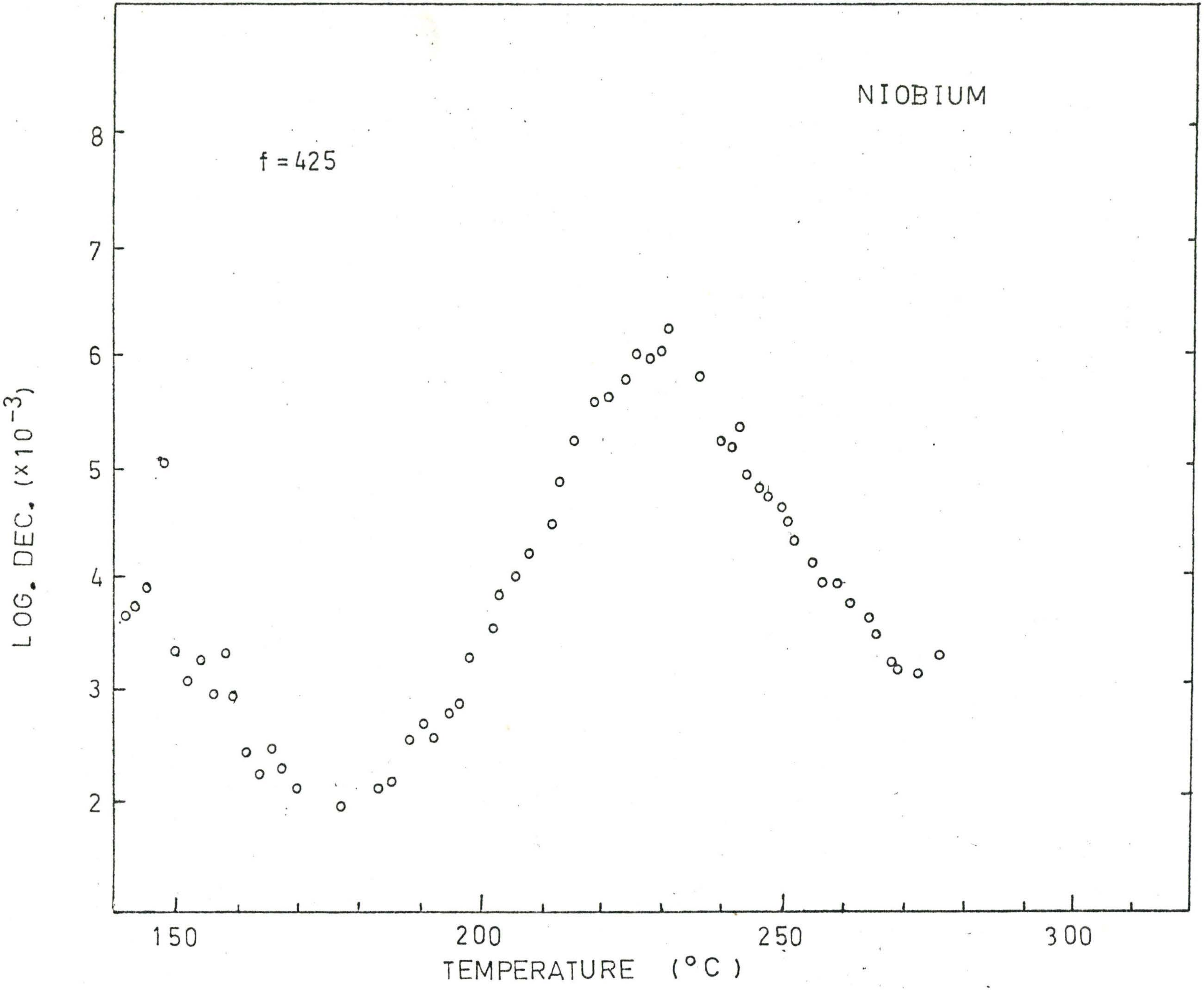

Fig. 9: I.F. spectrum for niobium (marz grade) in the temperature range of 140° to 280°C.