APPENDIX

APPENDIX - I

MICROINDENTATION HARDNESS OF INDIUM ANTIMONIDE CRYSTALS

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INDIUM ANTIMONIDE CRYSTALS

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A.1 INTRODUCTION

Of all the III - V compound semiconductors, Indium antimonide is easy to grow and its technology is advanced to the state that it could compare well in impurity content with the purest germanium and silicon. It is an almost ideal vehicle for conducting work in the study of band structure, effective masses, crystal binding and transport properties. Since the discovery of the semiconducting properties of InSb in 1950, a large amount of information is now available.[1-4] With the invention of the semiconductor laser and discovery of the Gunn effect, there is now an increased prospect of the industrial application of III - V compounds.

Indium antimonide is a stoichiometric compound with a zinc blende structure and chemical formula InSb. Some important properties and information about it is collected in table Ao. The hardness formulae derived in a phenomenological manner by a systematic detailed study of hardness of single crystals of alkali halides (KCl[5], KBr[6]), of rhombohedral crystals (Calcite[5,6,7], sodium nitrate in the present work), of metallic crystals (Zinc[6]) and ferro electric crystals (TGS[6]) are now firmly established for predicting quench hardness of crystalline materials. The present study of hardness of single crystals of Indium antimonide is to verify the hardness formulae derived for single crystals of above materials.

Table Ao

GENERAL INFORMATION OF INDIUM ANTIMONIDE

Chemical formula	:	InSb
Crystal structure	:	Zinc blende type, Layered crystal, Lattice constant 6.5 A at 300°K.
Melting point	:	535°C (under atmospheric pressure)
Crystal Growth	:	CZochralski method (Gatos 1960)
Growth Direction	:	[111] and [112]
Electron Density	:	10^{13} to 10^{16} per cm^3
Hardness of Indium	:	Between 3 and 3.5 on Moh's scale.
Hardness of Antimony	:	1.2 on Moh's scale
Mechanical property	:	Soft, Brittle, cleavage (111)
Valence electrons of Antimony atom	:	5
Valence electrons of Indium atom	:	3
Electron density	:	10^{13} to 10^{16} per cm^3
Band gap at 77°K	:	0.43 ev
Effective mass of electron	:	0.013 m^+

Effective mass of Hole	:	0.4 m[+]
Effective charge	:	0.42 e, - 0.45 e, 0.16 e[++]
Spin-orbit splitting	:	0.81 ev
Electron mobility at 300^oK (μ_n)	:	7×10^4 cm^2/V-S
Hole mobility at 300^oK (μ_p)	:	7×10^2 cm^2/V-S
Ratio b $(=\mu_n/\mu_p)$	:	100

Refractive Index at λ = 0.620 micron = 4.29

Extinction Coefficient at λ = 0.620 micron = 1.83

Reflectance Coefficient at λ = 0.620 micron = 0.453

+ m = Mass of free electron

e = Charge of free electron

+ from other method

++ The Callen effective charge

A.2 EXPERIMENTAL

Small crystal cleavages from one big single crystal were used in the present study. Every time freshly cleaved blocks of appropriately 8 mm x 5 mm x 1 mm size were used for hardness studies. Precautions such as use of almost identical sizes of treated and untreated samples, fixing and levelling of cleaved block on glass plate, spacing between two consecutive indentation marks on cleaved surface, indentation time, measurement of dimehsions of indentation marks, gradual heating of a sample to a desired temperature and quenching it to room temperature etc. (cf. Chapter V) were scruplously observed in the present work. The maximum temperature for quenching experiments for this crystal was 633°K. Since InSb gets oxidised in air ; experiments on thermal treatment were carried out by keeping sample in inert (Hydrogen) atmosphere (Worth 1962) or in vacuum. The indentation marks for applied loads varying from 1.25 gm to 120 gm were produced by square based Vickers pyramidal indenter on the freshly cleaved surface in such a manner that one of the diagonals of the mark was always parallel to crystal edge.

The study of the variation of diagonal length of indentation mark with applied load on cleavage faces of indium antimonide (Panchal 1981) has led to conclusions which are almost identical with those obtained from a corresponding study of synthetic single crystals of sodium nitrate (cf. Chapter V). The empirical equations used in the above analysis is Meyer's law

$$P = a\, d^n \qquad \ldots\ldots (1)$$

$$\text{or } \log P = n \log d + \log a \quad \ldots\ldots (2)$$

where d is diagonal length of indentation mark produced by an applied load P ; a is standard hardness and the exponent n is a constant ; both are characteristics of material.

A.3 VARIATION OF HARDNESS WITH LOAD

It is now well established from a study of hardness of synthetic single crystals of sodium nitrate and other crystals that 'standard hardness', 'a' is a function of quenching temperature ; 'a_1' and 'a_2' in general vary with quenching temperature (T_Q). It is now interesting and useful to study in detail how hardness changes with quenching temperature for InSb crystals.

The Vickers hardness number is defined by equation, (Mott, 1956)

$$H_v = 1854.4(P/d^2) \qquad \ldots\ldots (3)$$

where load P is measured in grams and diagonal length d, of the indentation mark in microns. The hardness number is not an ordinary number, but a constant having dimensions and a deep, but less understood physical meaning. The present work is a quantitative study of effect of quenching temperature on hardness. It is basically a phenomenological study of the problem.

A.3.1 Observations

The observations which were recorded for studying the equation, $P = a\ d^n$ are used in the present investigation (Table A-1,2) for thermally treated and untreated samples. The observations are graphically studied by plotting the graphs of hardness number versus load P (Fig. A-1, 2, 3, 4, 5, 6). In what follows the hardness and hardness number will be used to indicate same meaning.

A.3.2 Results and discussion

It is clear from the graphs of hardness number (H) versus load (P) that contrary to theoretical expectations (cf. Chapter IV), the hardness varies with load. The hardness at first increases with load, reaches a maximum value then gradually decreases, and attains a constant value for all loads. This behaviour is also found for both types of hardness number viz. Knoop hardness number (H_k) and Vickers hardness number (H_v) in case of sodium nitrate crystal (cf. Chapter VI) and calcite crystal

Table A-1

QUENCHING TEMPERATURE T_Q °K		306	375	444	495	578	633
LOAD P gm	Log P			Log d			
1.25	0.0969	0.7078	0.6978	-	0.7497	-	-
2.5	0.3979	0.8047	0.7497	0.7947	0.7835	0.8062	0.8347
3.75	0.5740	0.8746	0.7854	0.8013	0.7971	0.8115	-
5.0	0.6990	0.8853	0.8282	0.8512	0.8597	0.8633	0.8687
7.5	0.8751	0.9297	0.8746	0.8948	0.9148	0.8865	0.8919
10.0	1.0000	0.9424	0.9205	0.9360	0.9831	0.9518	0.9424
15.0	1.1761	1.0335	1.0460	1.0382	1.0172	1.0212	1.0000
20.0	1.3010	1.0900	1.1243	1.1179	1.1118	1.1038	1.0864
30.0	1.4771	1.2004	1.1936	1.1958	1.1853	1.1875	1.1722
40.0	1.6021	1.2757	1.2595	1.2636	1.2561	1.2557	1.2558
60.0	1.7782	1.3671	1.3547	1.3604	1.3611	1.3539	1.3463
80.0	1.9031	1.4270	1.4222	1.4211	1.4150	1.4134	1.4102
100.0	2.0000	1.4711	1.4930	1.4729	1.4625	1.4598	1.4506
120.0	2.0792	1.5068	1.5252	1.5115	1.5259	1.5034	1.4911

Table A-2

QUENCHING TEMPERATURE $T_Q\,^oK$	306	375	444	495	578	633
LOAD P gm	VICKERS HARDNESS NUMBER $H_v = 1854.4\ P/d^2$ $Kg - mm^{-2}$					
1.25	88.66	93.23	-	73.41	-	-
2.50	113.94	146.81	119.29	125.62	113.18	99.25
3.75	123.88	186.87	173.65	177.04	165.51	-
5.0	157.27	204.52	183.93	176.92	173.99	169.72
7.50	192.27	247.75	225.69	205.93	234.57	228.83
10.0	241.76	267.39	249.00	200.44	231.50	241.76
15.0	238.38	225.06	233.26	257.01	252.29	277.05
20.0	245.07	209.21	215.45	221.68	229.94	249.15
30.0	221.09	228.08	225.69	236.95	234.57	251.70
40.0	208.40	224.56	221.20	228.05	228.20	228.37
60.0	205.16	217.27	211.50	210.94	218.03	225.78
80.0	207.63	212.27	213.30	219.38	221.12	224.30
100.0	211.79	207.39	210.00	220.38	223.01	232.80
120.0	215.67	198.12	211.05	197.53	219.10	231.82

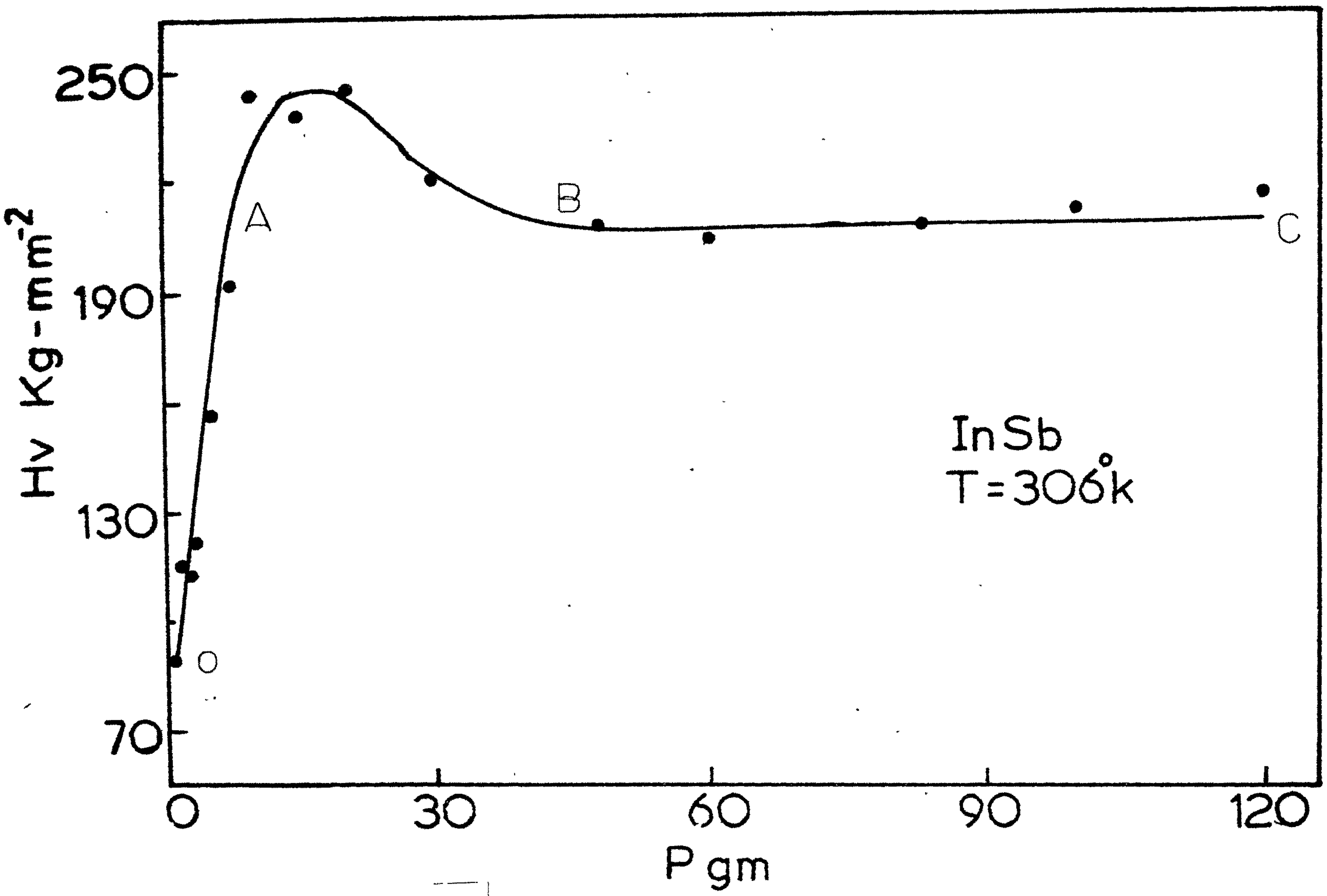

FIG. A. 1 PLOT OF Hv vs P

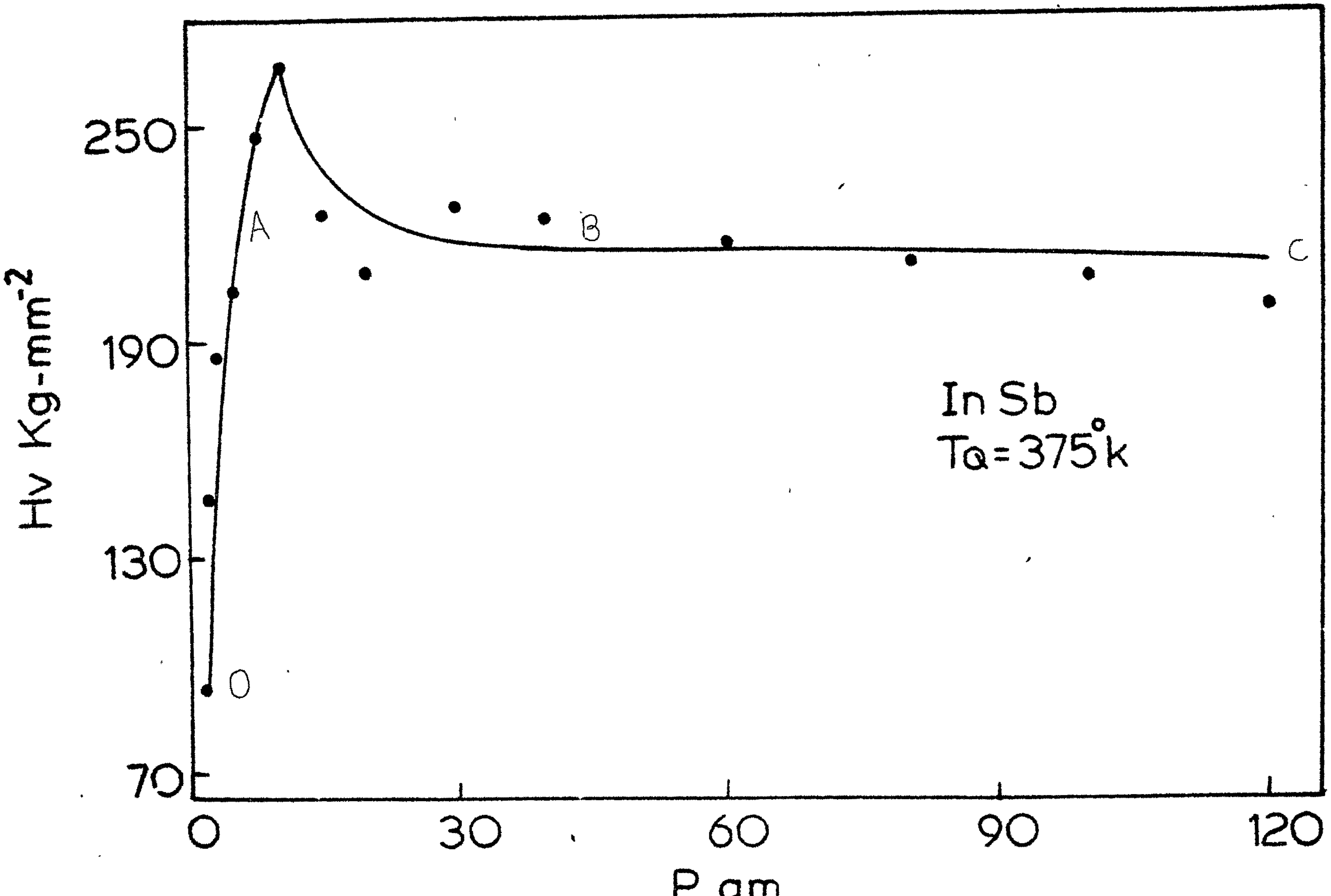

FIG. A· 2 PLOT OF Hv vs P

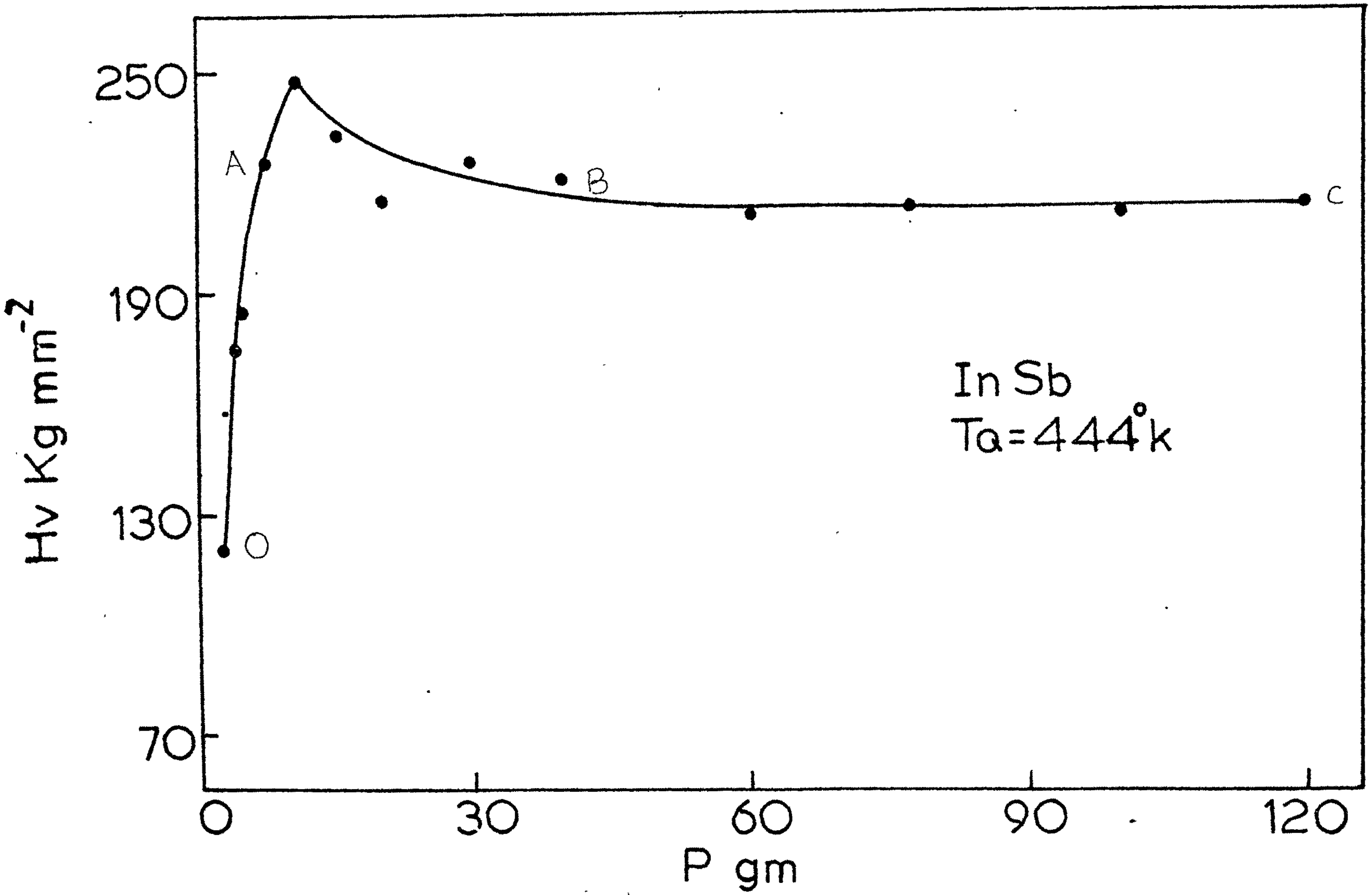

FIG. A·3 PLOT OF Hv vs P

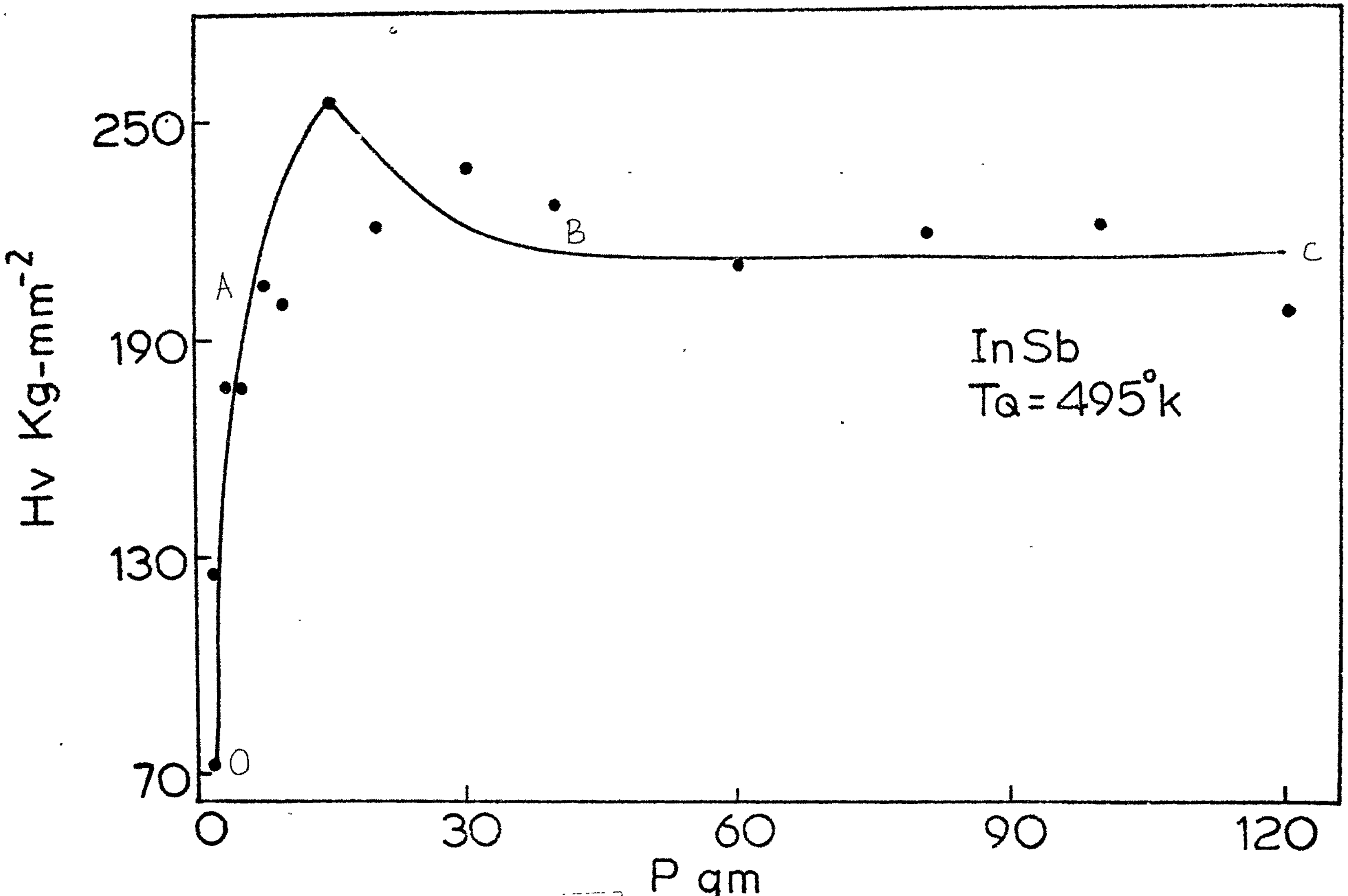

FIG. A·4 PLOT OF Hv vs P

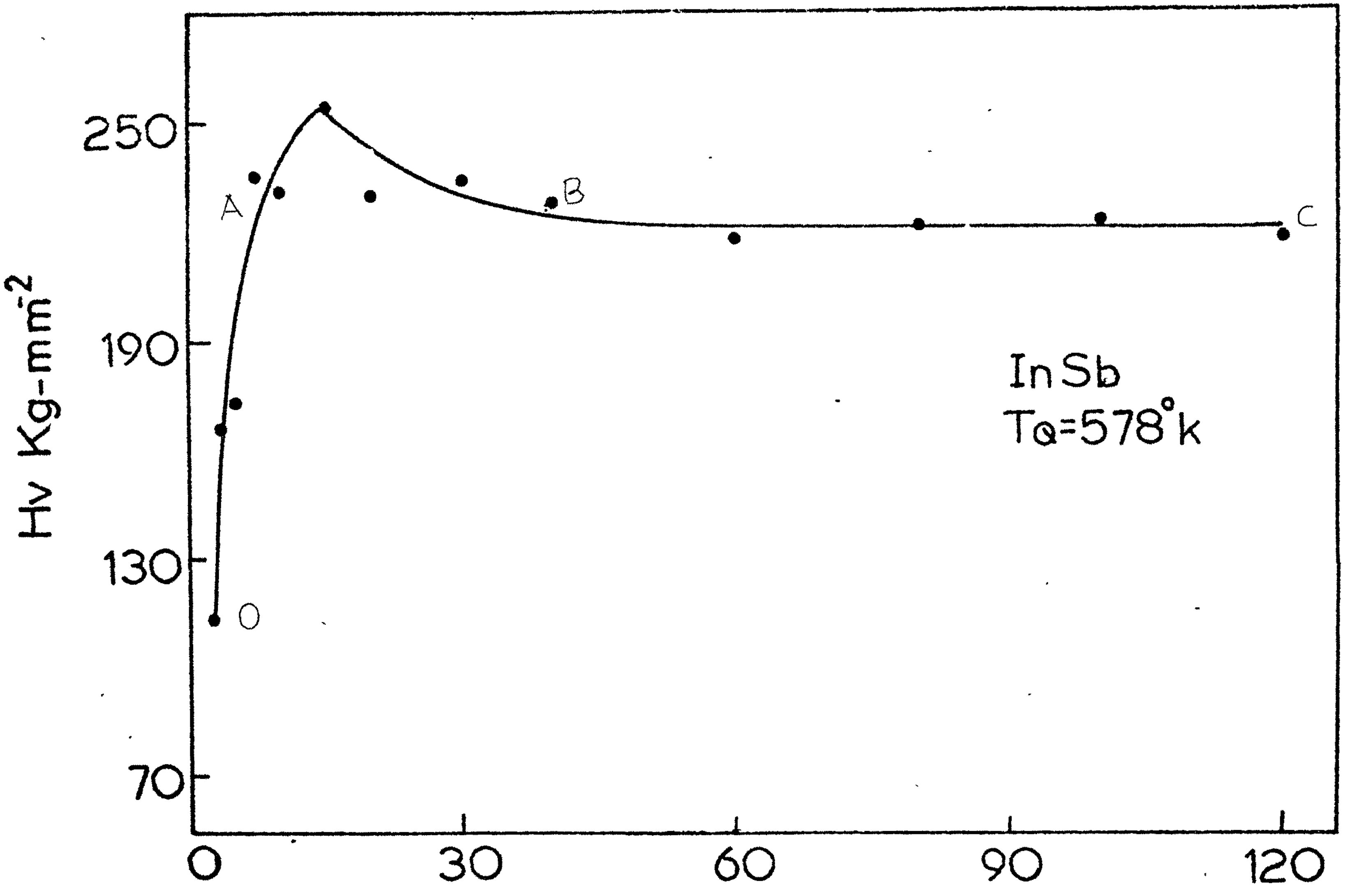

FIG. A· 5 PLOT OF Hv vs P

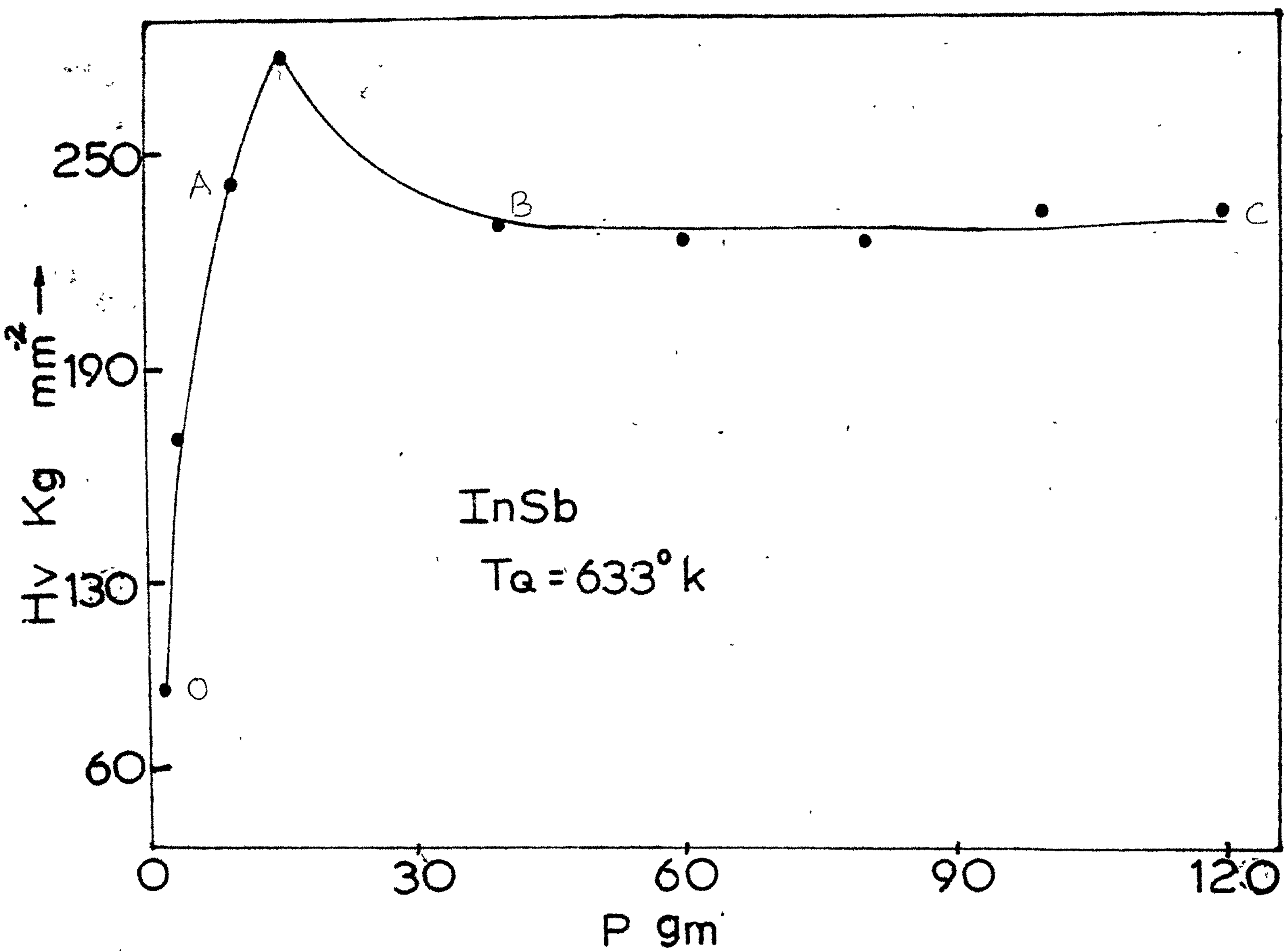

FIG: A 6 PLOT OF Hv vs LOAD

(Bhagia 1983). The theoretical conclusion that hardness is independent of load is true only at higher loads. The maximum value of hardness corresponds with a load which is nearer the value of the load at which the kink in the graph of log P versus log d is observed (Panchal 1981). The graph of H_V versus P can be conveniently divided into three parts OA, AB and BC where the first part represents linear relation between hardness and load, the second part, the non-linear relation and the third part the linear one. It should be noted that there is a fundamental difference between linear portions OA and BC of the graph OABC. This possibly reflects varied reactions of the cleavage surface to loads belonging to different regions. Besides it supports, to a certain extent, the earlier view about the splitting of the graph of log P versus log d into two recognizable lines (Panchal 1981).

The complex behaviour of microhardness with load can be explained on the basis of the depth of penetration of the indenter. At small loads the indenter penetrates only surface layers, hence the effect is shown more sharply at those loads. However, as the depth of impression increases, the effect of surface layers becomes less dominant and after a certain depth of penetration, the effect of inner layers becomes more and more prominent than those of surface layers and ultimately there is practically no change in value of hardness with load.

A.3.3 Relation between hardness and temperature of quenching

It is clear from the observations of hardness of quenched and unquenched samples (Table A-2) that hardness depends upon the quenching temperature (T_Q). Hardness in high load region (HLR) is independent of load. Hence average values of hardness ($\bar{H}$) in high load region are computed and are recorded in Table A-3, Fig. A-7 shows the plot of log ($\bar{H}$ T_Q) versus log T_Q. The plot is a straight line. The straight line follows the equation,

$$\log \bar{H}\, T_Q \;=\; m \log T_Q + \log C \qquad \text{..... (4)}$$

where m is the slope and C is a constant. Therefore,

$$\bar{H}\, T_Q^{\,1-m} \;=\; C \qquad \text{..... (5)}$$

or,

$$\bar{H}\, T_Q^{\,k} \;=\; C \qquad \text{..... (6)}$$

where $k = 1 - m$. The value of k is $- 0.11$ for Indium Antimonide (Table A-3). It is clear from table that Vickers hardness number in HLR increases with temperature of quenching. However the percentage increase in hardness with respect to hardness at room temperature (306°K) is quite small.

TABLE A-3

QUENCHING TEMPERATURE $T_Q^{o}K$	Log T_Q	AVERAGE HARDNESS IN HLR $\bar{H}$ kg. mm^{-2}	Log $\bar{H}$ T_Q	$\bar{H}$ $T_Q^{-0.11}$ = C	% DEVIATION OF C FROM MEAN VALUE	% DEVIATION OF C FROM VALUE OF C FROM GRAPH
306	2.4857	209.73	4.8073	111.10	+ 1.230	+ 0.234
375	2.5740	211.92	4.9000	109.76	+ 0.009	- 0.974
444	2.6474	213.21	4.9761	108.38	- 1.240	- 2.219
495	2.6946	215.25	5.0275	108.10	- 1.503	- 2.472
578	2.7619	221.80	5.1071	109.49	- 1.237	- 1.217
633	2.8014	228.61	5.1605	111.72	+ 1.790	- 0.794

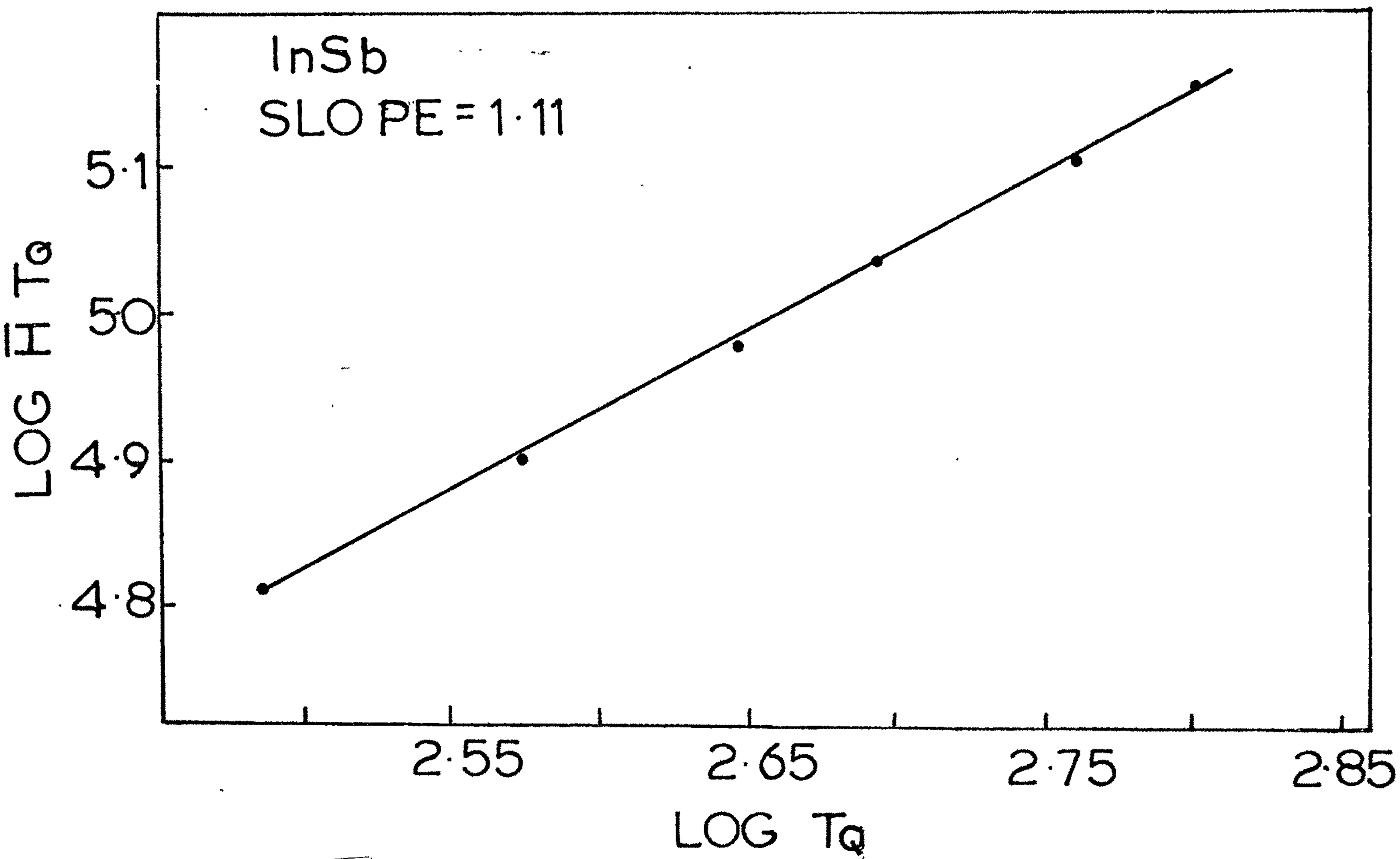

FIG A·7 PLOT OF LOG $\bar{H}T_q$ VS LOG T_q

It is desirable to ascertain how far the relation $\bar{H}\ T_Q^k$ = constant is true for individual observations on quench hardness. This constant is designated by C (Table A-3). The percentage deviation of C from mean value and from graph are small. From empirical formula for Vickers hardness number it is obvious that hardness number is inversely proportional to square of the diagonal of the indentation mark for a constant load. Since hardness depends on temperature of quenching, the diagonal length of the indentation mark would also depend on the temperature of quenching. Thus

$$H = R\ .(P/d^2) \qquad \ldots\ldots (7)$$

where R is a constant depending upon the geometry of the indenter. Further,

$$H\ T_Q^k = C \qquad \ldots\ldots (8)$$

Combination of above equations gives,

$$\frac{P\ T_Q^k}{d^2} = \frac{C}{R} = \text{Constant} = S \qquad \ldots\ldots (9)$$

or,

$$\frac{T_Q}{d^2} \times P\ T_Q^{k-1} = S \qquad \ldots.. (10)$$

$$\frac{T_Q}{d^2} = \frac{S}{P} \quad T_Q^{1-k} \qquad \ldots\ldots (11)$$

or

$$\log \frac{T_Q}{d^2} = \log (S/P) + (1 - k) \log T_Q \ldots\ldots (12)$$

Let $S/P = A, \; m_1 = (1 - k) \qquad \ldots\ldots ($

Hence equation (12) becomes

$$\log \frac{T_Q}{d^2} = m_1 \log T_Q + \log A \qquad \ldots\ldots (13)$$

$$\frac{T_Q^{1 - m_1}}{d^2} = S/P = A \qquad \ldots\ldots (14a)$$

Utilization of equations (7), (8) and (14)a gives,

$$\frac{T_Q}{d^2} = \frac{C}{RP} \qquad \ldots\ldots (14b)$$

It is obvious from the above equation 13 that for a given applied load if a graph of log (T_Q/d^2) is plotted against log T_Q, the slope of graph will be $(1 - k)$. However if this is repeated for several applied loads, it is evident from the above equation that graph of log (T_Q/d^2) versus log T_Q should consist of straight lines parallel to one another having slope $(1 - k)$ and different intercepts.

Further, the slope of plot (Fig. A-8 ; Table A-4) is 1.11

$$i.e. \quad 1 - k = m_1 = 1.11$$

Hence the value of k is - 0.11 which is identical with the value of the exponent k in the equation (8) connecting hardness number and quenching temperature.

It was reported that'a' and 'n' are constants and the straight line represented by the plot of log P versus log d consisted of two straight lines with slopes n_1 and n_2 and intercepts 'a_1' and 'a_2' respectively (Panchal 1981 Table A-5). The combination of equations 1 and 9 yields

$$\frac{a_2 d^{n_2} T_Q^{k}}{d^2} = S \quad \ldots\ldots (15)$$

substituting

$$d^2 = (P/a_2)\, d^{n_2 - 2} \quad \ldots\ldots\ldots\ldots (16)$$

in eq. 14a, one gets

$$\frac{T_Q^{1 - m_1}}{P} \times a_2\, d^{n_2 - 2} = A \quad \ldots\ldots (17)$$

Since n_2 is not having an integral value, it is necessary to have a different approach. If graph of

Table A-4

QUENCHING TEMPERATURE $T_Q^o K$	306	373	444	495	578	633
LOAD P gm				Log (T_Q/d_v^2)		
40	$\bar{1}.9342$	0.0555	0.1201	0.1823	0.2504	0.2890
60	$\bar{1}.7518$	$\bar{1}.8650$	$\bar{1}.9265$	0.7175	0.0541	0.1087
80	$\bar{1}.6316$	$\bar{1}.7318$	$\bar{1}.8051$	$\bar{1}.9723$	$\bar{1}.9350$	$\bar{1}.9809$
100	$\bar{1}.5434$	$\bar{1}.5879$	$\bar{1}.7016$	$\bar{1}.8646$	$\bar{1}.8429$	$\bar{1}.9002$
120	$\bar{1}.4722$	$\bar{1}.5236$	$\bar{1}.6244$	$\bar{1}.7698$	$\bar{1}.7551$	$\bar{1}.8192$

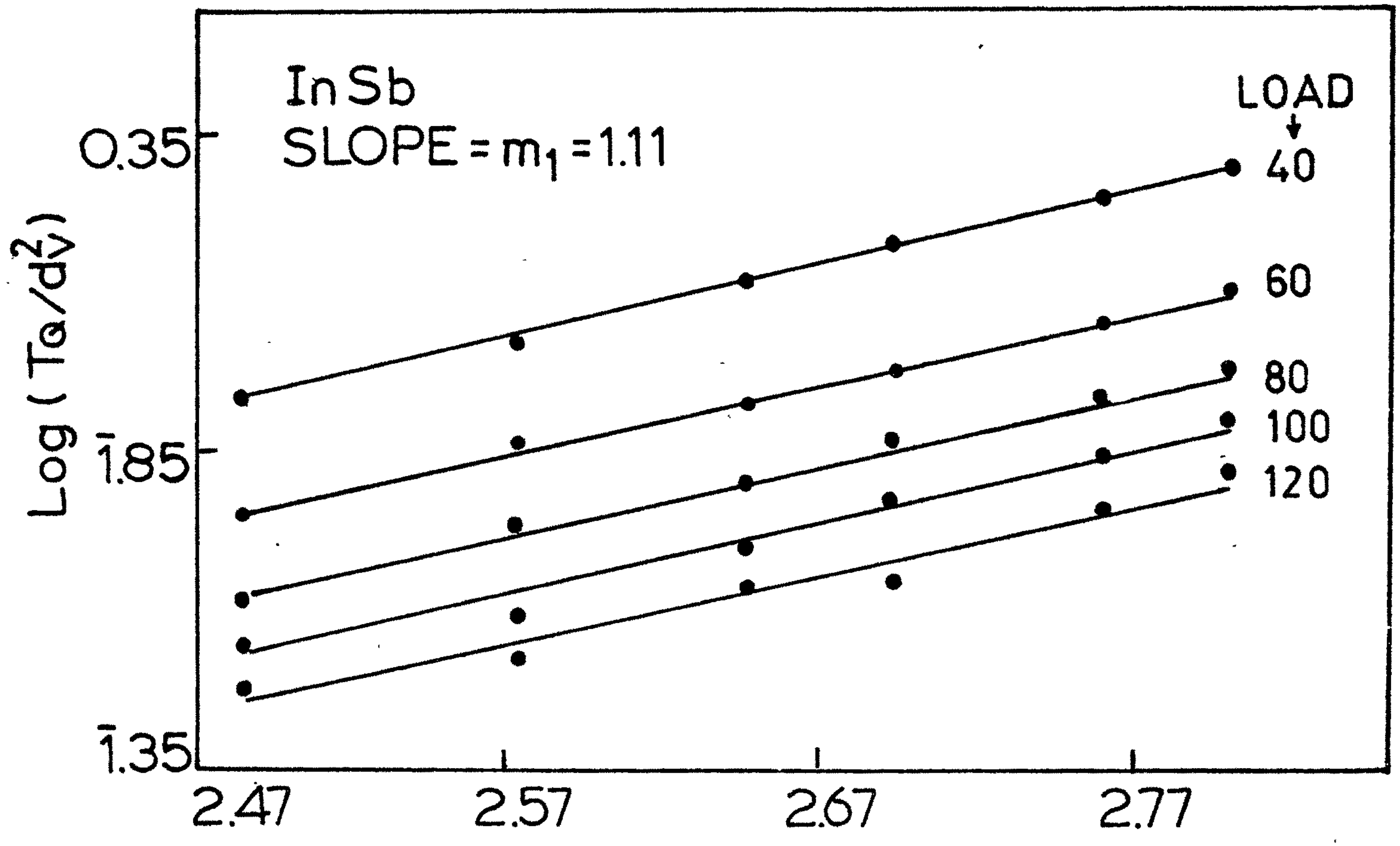

FIG. A· 8 PLOT OF LOG T_Q/d_V^2 vs LOG T_Q

Table A-5

QUENCHING TEMPERATURE T_Q°K	Log T_Q	LOW LOAD REG.		HIGH LOAD REG.		$Log(a_2 T_Q)$	$a_2 T_Q^{-0.08} = D$	LOAD AT KINK P gm
		n_1	$a_1 \times 10^{-3}$	n_2	a_2			
306	2.4857	3.75	2.44	1.9	0.1555	1.6774	0.09837	10
375	2.5740	3.42	7.08	1.9	0.1558	1.7748	0.09883	10
444	2.6474	3.52	5.14	1.9	0.1596	1.8504	0.09800	10
495	2.6946	3.33	6.94	1.9	0.1639	1.9092	0.09977	10
578	2.7619	3.87	2.27	1.9	0.1650	1.9794	0.09920	15
633	2.8014	4.8	0.29	1.9	0.1674	2.0251	0.09991	15

log $(a_2 d^2/T_Q)$ versus log T_Q is plotted, it consists of a series of parallel lines corresponding to different intercepts (Table A-6 ; Fig. A-9). Thus each straight line follows the general equation,

$$\log \frac{a_2 d^2}{T_Q} = m_2 \log T_Q + \log B \quad \ldots\ldots (18)$$

Slope of each straight line is $m_2 = -1.031$. Simplification of the above equation yields,

$$a_2 d^2 T_Q^{0.031} = B \quad \ldots\ldots\ldots (19)$$

Combination of above equation with eqn. (1) gives

$$P d^{2-n_2} T_Q^{0.031} = B \quad \ldots\ldots (20)$$

Comparison of Meyer's law (eqn. 1) with formula for hardness (eqn. 3) clearly suggests that the constant 'a' and hardness number are related. Inspection of the variation of various functions involving H, a_2 and T_Q indicates that graph of log $(\bar{H} T_Q/a_2)$ versus log T_Q would be a straight line following the equation,

$$\log \frac{\bar{H} T_Q}{a_2} = m_3 \log T_Q + \log E \quad \ldots\ldots (21)$$

where slope is given by $m_3 = 1.022$ and E is constant. This plot for Vickers hardness numbers is presented in fig. A.10 (Table A.7).

Table A-6

QUENCHING TEMPERATURE T_{ℓ} °K	306	373	444	495	578	633
LOAD P gm			Log $(a_2 d_v^{\,2}/T_{\ell})$			
40	$\bar{1}.2573$	$\bar{1}.1433$	$\bar{1}.0812$	$\bar{1}.0324$	$\bar{2}.9669$	$\bar{2}.9327$
60	$\bar{1}.4398$	$\bar{1}.3335$	$\bar{1}.2748$	$\bar{1}.2425$	$\bar{1}.1630$	$\bar{1}.1136$
80	$\bar{1}.5598$	$\bar{1}.4668$	$\bar{1}.3962$	$\bar{1}.3501$	$\bar{1}.2824$	$\bar{1}.2418$
100	$\bar{1}.6481$	$\bar{1}.6105$	$\bar{1}.4998$	$\bar{1}.4450$	$\bar{1}.3751$	$\bar{1}.3224$
120	$\bar{1}.7191$	$\bar{1}.6749$	$\bar{1}.5769$	$\bar{1}.5718$	$\bar{1}.4622$	$\bar{1}.4034$

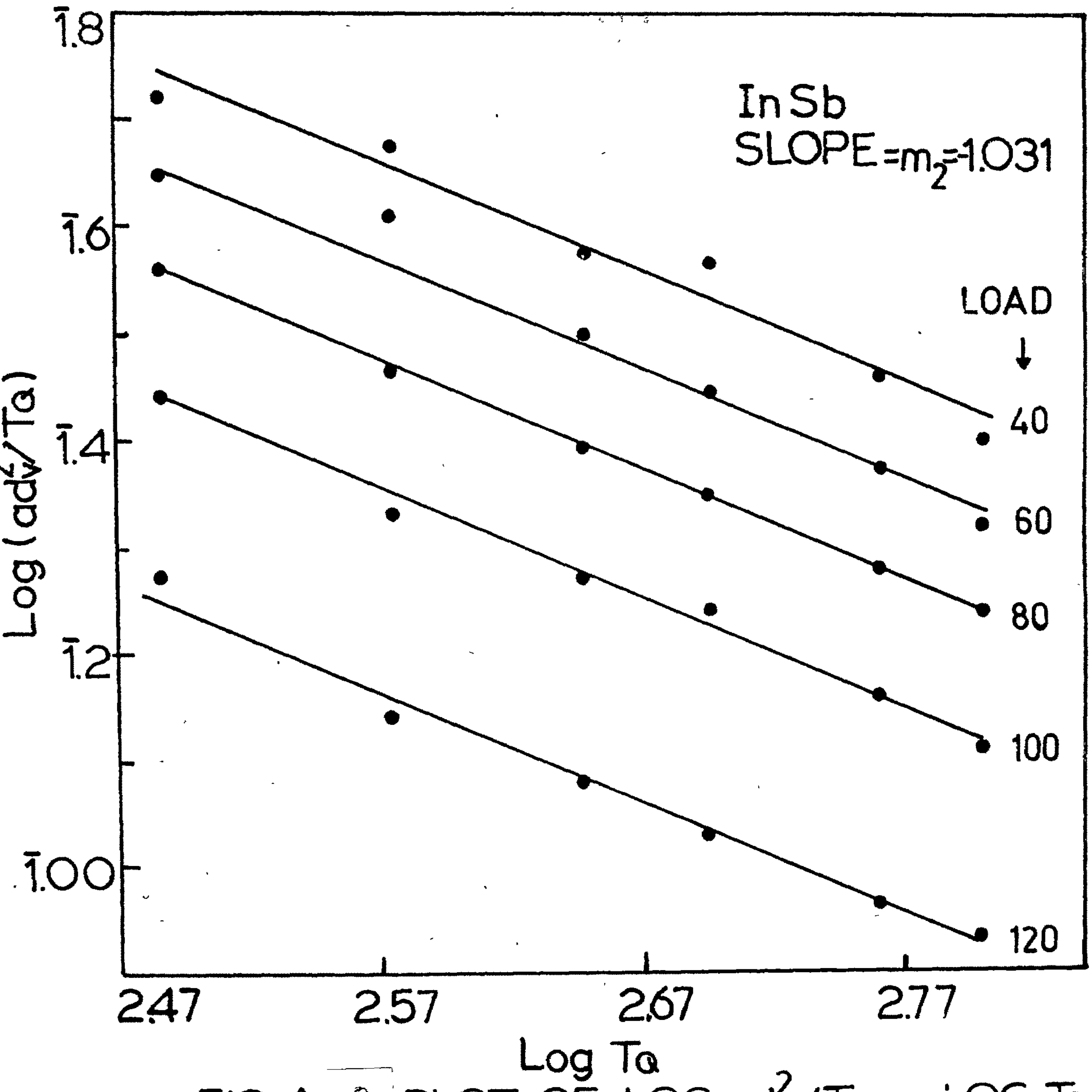

FIG. A· 9 PLOT OF LOG ad_v^2/T_a vs LOG T_a

Table A-7

QUENCHING TEMPERATURE T_Q °K	Log T_Q	Log $\bar{H}$	Log $(a_2\bar{H})$	Log $(\frac{\bar{H}\,T_Q}{a_2})$	$E = (\bar{H}\,T_Q/a_2)^{-0.0226}$
306	2.4857	2.3216	1.5134	5.6157	1185.09
375	2.5740	2.3261	1.5270	5.7015	1167.21
444	2.6474	2.3288	1.5318	5.7748	1163.97
495	2.6946	2.3329	1.5475	5.8127	1141.47
578	2.7619	2.3459	1.5634	5.8905	1164.28
633	2.8014	2.3591	1.5828	5.9378	1180.31

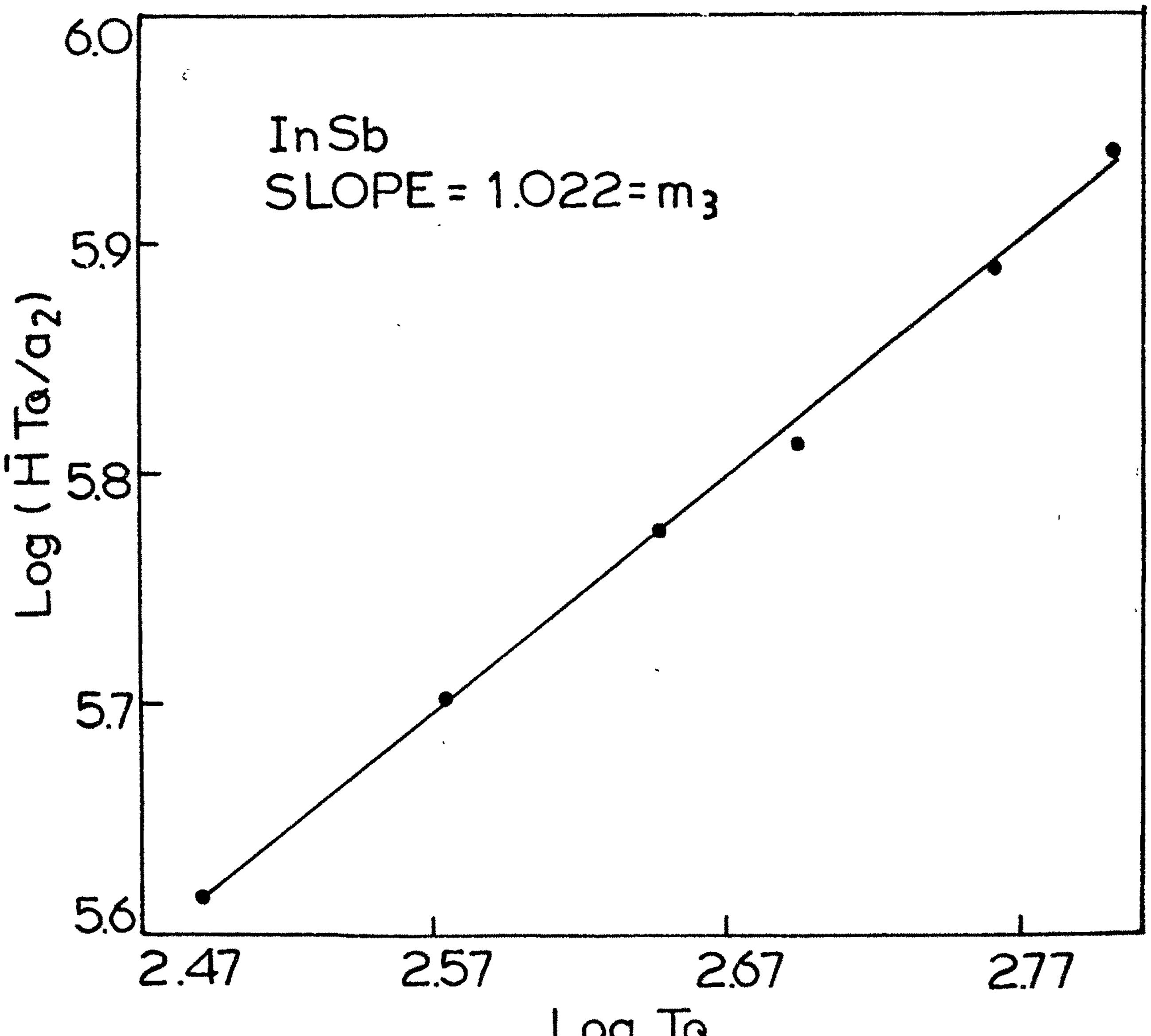

FIG. A· 10 PLOT OF LOG H T_a/a_2 vs LOG T_a

Substitution of $a_2 = (P/d^2)\ d^{2 - n_2}$ and

$$H = R(P/d^2) \text{ in eqn. (21)}$$

yields,

$$E = R\ T_Q^{1 - m_3}\ d^{n_2 - 2} \qquad \text{..... (22)}$$

simplifying eqn. 21, gets

$$\frac{\bar{H}\ T_Q^{1 - m_3}}{a_2} = E \qquad \text{......(23)}$$

i.e.

$$\frac{\bar{H}\ T_Q^{-0.022}}{a_2} = E \qquad \text{..... (24)}$$

multiplication of eqn. 17 with eqn. 20 gives

$$T_Q^{k} \cdot a_2\ d^{n_2 - 2} \cdot P\ d^{2 - n_2} \cdot T_Q^{0.031} = AB \times P$$

or,

$$a_2\ T_Q^{(k + .031)} = AB = \text{Constant} \quad \text{...(25)}$$

Thus the intercepts a_2 could be associated with the quenching temperature. This can also be understood from a graphical plot of log $(a_2\ T_Q)$ versus log T_Q which follows the equation,

$$\log (a_2 T_Q) = m_4 \log T_Q + \log D \qquad \ldots\ldots (26)$$

The graph of log (a_2 T_Q) versus log T_Q is shown in figure A-11 (Table A-5).

Thus,

$$a_2 T_Q^{1 - m_4} = D \qquad \ldots\ldots (27)$$

where m_4 is the slope of fig. A-11 and equals 1.08.

Hence the above equation becomes

$$a_2 T_Q^{-0.08} = D \qquad \ldots\ldots (28)$$

substitution of

$a_2 = P/d^2 \cdot d^{2 - n_2}$ in equation (27)

yields,

$$\frac{P}{d^2} \cdot d^{2 - n_2} \cdot T_Q^{1 - m_4} = D \qquad \ldots\ldots (29)$$

Slight dependence of a_2 on quenching temperature can be expected because value of a_2 (Table A-5) is quite small. It is suggested from the form of eqn. (1) and eqn. (7) that there must be some relation between hardness number and a_2. After considering several functions containing H and a_2 it was found that the plot of log (a_2 $\bar{H}$) versus

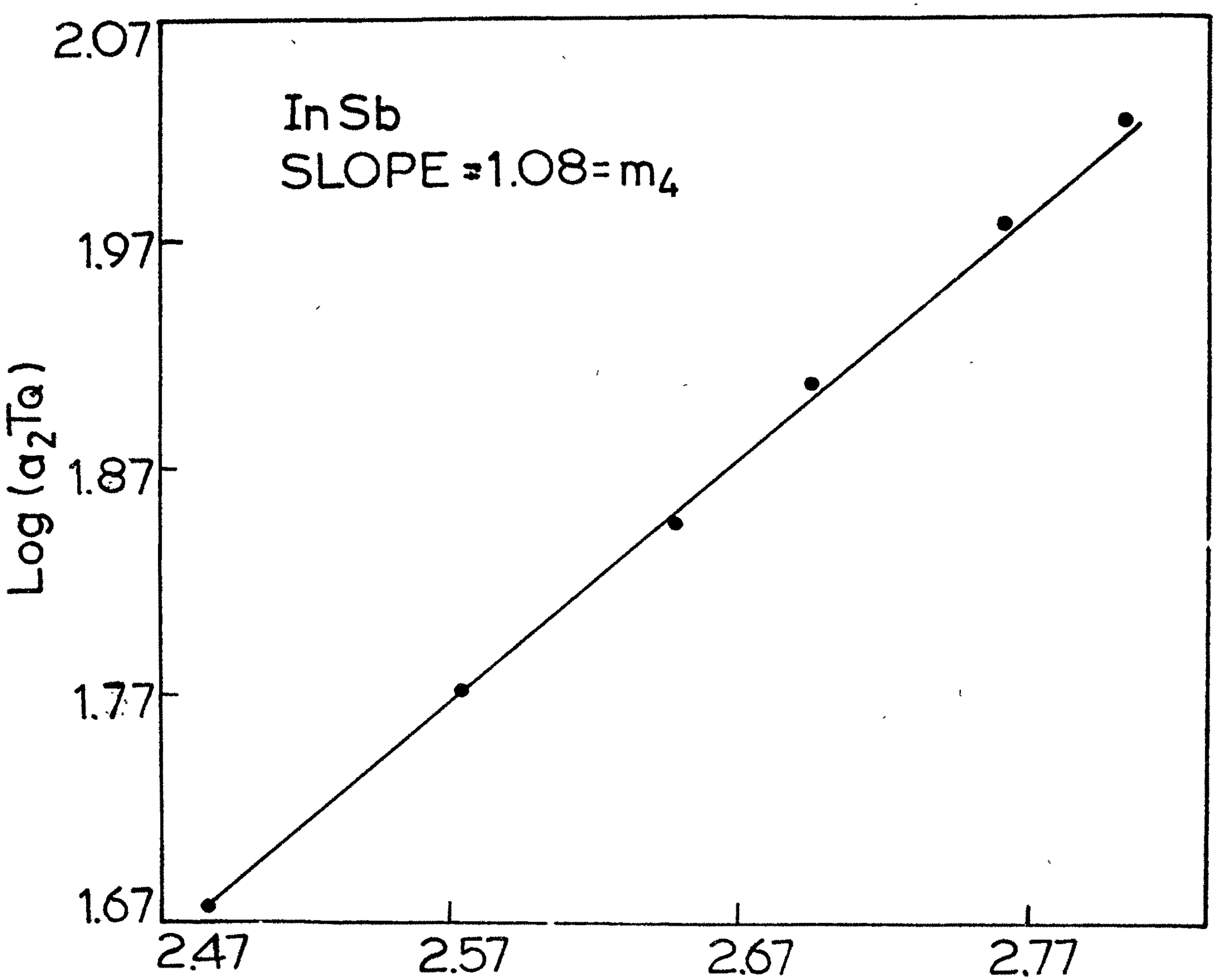

FIG. A·11 PLOT OF LOG a_2T_a vs LOG T_a

log $\bar{H}$ gives a better straight line, obeying the general equation

$$\log (a_2 \bar{H}) = m_5 \log \bar{H} + \log F \qquad \ldots\ldots (30)$$

Hence,

$$a_2 \bar{H}^{1 - m_5} = F \qquad \ldots\ldots (31)$$

slope of the above plot (fig. A-12) is given by $m_5 = 1.779$. Substitution of value of m_5 in eqn. 31 gives,

$$a_2 \bar{H}^{- 0.779} = F \qquad \ldots\ldots (32)$$

This shows very clearly that hardness number and the intercept of the straight line (cf. fig. A-12) corresponding to HLR are intimately connected, thereby indicating connection of Meyer's law with hardness number.

It is interesting to examine the accuracy of each observation in the above plots by considering the coefficient of variation for different constants associated with different equations mentioned above.

The values of A, B, E and D are compared for each observation using equations 17, 19, 22, 29 respectively and are presented in Tables A-8.1 to A-8.6. For these

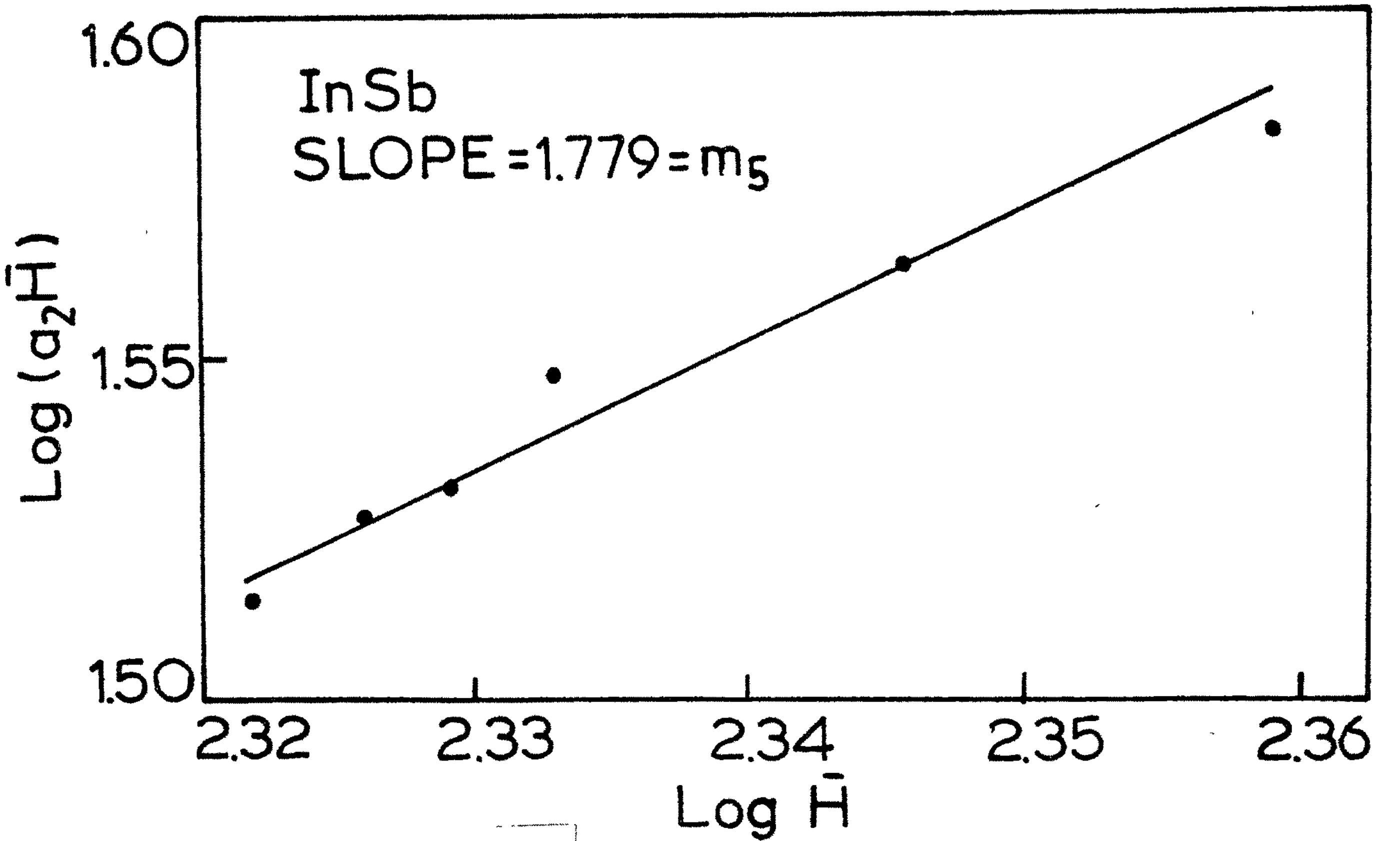

FIG. A·12 PLOT OF LOG $a_2\bar{H}$ vs LOG T_Q

TABLE A.8.1

LOAD P gm	ROOM TEMPERATURE 306 ^{o}K							
	A x 10^{-3}	B	AB x 10^{-2}	D x 10^{-2}	P/B	AP x 10^{-2}	E	(DE/1854.4) x 10^{-2}
40	1.544	64.07	9.892	9.536	0.6243	6.176	1214.6	6.246
60	1.008	98.15	9.892	9.588	0.6113	6.047	1189.3	6.149
80	0.745	132.1	9.891	9.838	0.6029	5.964	1173.1	6.309
100	0.590	167.6	9.892	10.14	0.5968	5.904	1161.2	6.223
120	0.488	202.7	9.892	10.41	0.5919	5.856	1151.7	6.347
MEAN	-	-	9.8918	9.9024	0.6054	5.9894	1177.98	6.2548

TABLE A.8.2

LOAD P gm	Quenching Temperature $375^{o}K$							
	$A \times 10^{-3}$	B	$AB \times 10^{-2}$	$D \times 10^{-2}$	P/B	$AP \times 10^{-2}$	E	$(DE/1854.4) \times 10^{-2}$
40	1.547	64.24	9.938	10.07	0.6226	6.188	1213.6	6.590
60	1.009	98.49	9.941	9.961	0.6091	6.056	1187.3	6.377
80	0.745	133.4	9.941	9.884	0.5997	5.962	1168.9	6.230
100	0.587	169.5	9.941	9.064	0.5900	5.866	1150.1	5.621
120	0.485	204.9	9.941	9.447	0.5856	5.822	1141.6	5.815
MEAN	-	-	9.9404	9.6852	0.6014	5.9788	1172.3	6.1266

TABLE A.8.3

LOAD P gm	QUENCHING TEMPERATURE $444^{o}K$							
	$\dot{A} \times 10^{-3}$	$\dot{B}$	$\dot{A}\dot{B} \times 10^{-2}$	$\dot{D} \times 10^{-2}$	$\dot{P}/\dot{B}$	$\dot{A}\dot{P} \times 10^{-2}$	$\dot{E}$	$(\dot{D}\dot{E}/1854.4) \times 10^{-2}$
40	1.525	64.648	9.859	9.757	0.6188	6.101	1207.8	6.355
60	0.994	99.14	9.859	9.585	0.6052	5.967	1181.2	6.105
80	0.736	134.1	9.859	9.799	0.5968	5.884	1164.8	6.155
100	0.581	169.6	9.859	9.765	0.5897	5.814	1151.0	6.061
120	0.480	205.3	9.858	9.898	0.5845	5.762	1140.8	6.089
MEAN	-	-	9.8588	9.7608	0.599	5.9056	1169.12	6.153

TABLE A.8.4

LOAD P gm	QUENCHING TEMPERATURE $495^{o}K$							
	$A \times 10^{-3}$	B	$AB \times 10^{-2}$	$D \times 10^{-2}$	P/B	$AP \times 10^{-2}$	E	$(DE/1854.4) \times 10^{-2}$
40	1.550	64.74	10.03	9.996	0.6178	6.200	1206.8	6.505
60	1.009	98.98	9.987	9.472	0.6062	6.054	1178.1	6.017
80	0.747	134.32	10.04	9.975	0.5956	5.978	1163.6	6.259
100	0.591	169.7	10.05	10.13	0.5891	5.914	1150.9	6.287
120	0.486	206.7	10.04	9.213	0.5806	5.827	1134.3	5.635
MEAN	-	-	10.0274	9.7572	0.5978	5.9946	1166.74	6.1406

TABLE A.8.5

LOAD P gm	QUENCHING TEMPERATURE 578 °K							
	A x 10^{-3}	B	AB x 10^{-2}	D x 10^{-2}	P/B	AP x 10^{-2}	E	(DE/1854.4) x 10^{-2}
40	1.535	65.05	9.983	9.888	0.6149	6.138	1202.8	6.413
60	1.000	99.81	9.982	9.654	0.6012	6.001	1175.9	6.122
80	0.740	134.9	9.982	9.921	0.5929	5.919	1159.9	6.205
100	0.586	170.4	9.982	10.12	0.5866	5.856	1147.6	6.262
120	0.483	206.6	9.983	10.04	0.5808	5.798	1136.2	6.151
MEAN	-	-	9.9822	9.9246	0.59528	5.9424	1164.48	6.2306

TABLE A.8.6

LOAD P gm	QUENCHING TEMPERATURE $633^{o}K$							
	A x 10^{-3}	B	AB x 10^{-2}	D x 10^{-2}	P/B	AP x 10^{-2}	E	(DE/1854.4) x 10^{-2}
40	1.541	65.23	10.05	9.813	0.6132	6.165	1200.3	6.357
60	1.006	99.91	10.05	9.907	0.605	6.038	1175.6	6.281
80	0.744	135.2	10.05	09.86	0.5918	5.949	1158.4	6.239
100	0.589	170.6	10.05	10.46	0.5863	5.895	1147.7	6.473
120	0.487	206.6	10.05	10.51	0.5808	5.840	1137.1	6.444
MEAN	-	-	10.05	10.1356	0.5954	5.9774	1163.82	6.3588

TABLE A.9

QUENCHING TEMPERATURE ^{o}K	AB x 10^{-2}	D x 10^{-2}	AP x 10^{-2}	$(\frac{DE}{1854.4}) \times 10^{-2}$	P/B	E	C	C/D
306	9.8918	9.9024	5.9894	6.2548	0.6054	1177.98	111.10	1121.95
375	9.9404	9.6852	5.9788	6.1266	0.6014	1172.30	109.78	1133.26
444	9.8588	9.7608	5.9056	6.1530	0.5990	1169.12	108.38	1110.36
495	10.0274	9.7572	5.9946	6.1406	0.5978	1166.74	108.10	1107.89
578	9.9822	9.9246	5.9424	6.2306	0.5953	1164.48	109.49	1103.22
633	10.05	10.1356	5.9774	6.3588	0.5954	1163.82	111.72	1102.25
MEAN	9.9584	9.8609	5.9647	6.2107	0.5991	1169.07	109.758	1113.15
COEFFICEENT OF VARIATION %	0.737	1.553	1.291	1.3494	0.6103	0.4821	1.2229	1.0529
VALUES FROM GRAPH	9.893	9.862	5.8954	6.208	0.5958	1167.4	110.84	1129.0

tables the above equations are rewritten here in sequence with new equation numbers.

$$A = \frac{T_Q^{1 - m_1}}{P} \cdot a_2\, d^{n_2 - 2} \qquad \ldots\ldots (33)$$

$$B = P \cdot d^{2 - n_2} \cdot T_Q^{0.031} \qquad \ldots\ldots (34)$$

$$\frac{P}{B} = \frac{d^{n_2 - 2}}{T_Q^{0.031}} \qquad \ldots\ldots (35)$$

$$AB = \frac{P\, T_Q^{k + 0.031}}{d^2} \qquad \ldots\ldots (36)$$

$$AP = T_Q^{1 - m_1} \cdot a_2 \cdot d^{n_2 - 2} \qquad \ldots\ldots (37)$$

$$D = \frac{P}{d^2} \cdot d^{2 - n_2} \cdot T_Q^{1 - m_4} \qquad \ldots\ldots (38)$$

$$E = R\, T_Q^{1 - m_3} \quad d^{n_2 - 2} \qquad \ldots\ldots (39)$$

$$DE = \frac{RP}{d^2} \cdot T_Q^{2 - m_3 - m_4} \qquad \ldots\ldots (40)$$

The mean values of constants are summarised in Table A-9.

A careful study of mean values of 'constants' and their deviations from the corresponding observations clearly indicates that the deviations are within experimental errors. A glance at Table A-9 shows that

$$D = AB \quad \ldots\ldots (41)$$

$$AP = DE/R \quad \ldots\ldots (42)$$

$$E = C/D \quad \ldots\ldots (43)$$

Thus for all loads in HLR, the variation of hardness number H and the variation of hardness constant a_2 with temperature of quenching and also with each other follows the equation,

$$H\, T_Q^{\,k} = C = \text{Constant} \quad \ldots\ldots (44)$$

$$a_2\, T_Q^{\,r} = D = \text{Constant} \quad \ldots\ldots (45)$$

$$a_2\, H^s = F = \text{Constant} \quad \ldots\ldots (46)$$

where k, r and s are numbers numerically less than unity. The signs for these constants decide the nature of the crystal. For Indium Antimonide they are negative as shown above. The constants in above equations have different values. Further quenching can also be carried out by bringing a crystal from very low temperature to room temperature. Thus for $T_Q = 1^{o}K$,

$$H = \text{Constant} \quad \ldots\ldots (47)$$

$$a_2 = \text{Constant} \quad \ldots\ldots (48)$$

These values can be considered to characterize a crystalline material. Thus for Indium Antimonide, the quench hardness number and quench hardness constants are given by

$$H = 109.758 \text{ kg} - \text{mm}^{-2} \quad \ldots\ldots (49)$$

$$a = 9.95 \text{ kg} - \text{mm}^{-2} \quad \ldots\ldots (50)$$

A.4 GRAPHICAL ANALYSIS OF OBSERVATIONS

It is clear from the general information on graphical analysis (cf. Chapter III) that there are basically 5 methods to obtain the estimation of the best straight line. In the present work the calculated values of hardness (represented by hardness number) in the high load region are combined with those of observed values of quenching temperature T_Q for obtaining a straight line plot between the variables Log $\bar{H}$ T_Q = y and Log T_Q = x (cf. Table A.3 and fig. A.7). The total number of observations in this table is six. The mean values of x ana y are given in table A.10A. The two pairs of extreme observations alongwith their spread from the corresponding mean values are given in this table. Further while drawing a graph by visual estimation the values of the pairs of extreme observation slightly change. These are also recorded alongwith a percentage change in their values from the slope of the straight line plot (fig. A.7). It is clear from this percentage change in the slope value that the quenching temperatures viz. 306 and 633^{O}K corresponding to those extreme observations have a significant effect on the slope value. This also suggests that these observations are unusual in the sense that inspite of taking all possible precautions in experimental work the same set of observations are obtained. The reasons are not yet clear.

Zero sum method is used to calculate the slope (cf. equation 3.3, Chapter III). It is noticeable that percentage change in the value of the slope from the one obtained from the plot (fig. A.7) is zero (Table A·10 B). Centroid methods are used to determine the slope for comparing it with the one obtained from the actual straight line. It should be remarked that the conditions viz. total number of observations and equal spacing of actually known variable which form the basis for calculating the slope, are not fully satisfied. However the percentage change in the value of the slope from the one actually determined from the graph is within experimental errors (Table A·10 C). In the method of estimation of best straight line by data used in specific manner, namely equal spacing of independent variable and multiplication of each straight line equation by the first 6 natural numbers in the sequence 1, 2, 3 .... 6, the conditions are not fully satisfied. However the difference between calculated value and graphical value of the slope is zero (Table A10 D). The statistical estimation of best straight line gives the regression coefficients (cf. equations 3.30 and 3.35, Chapter III) which are the calculated values of slopes. The percentage change of these values from the actual value of slope (Table A10 E) are small and within experimental errors.

The results of all these methods indicate that the experimental observations are reliable for carrying out the analysis. However the results of the first method, namely visual estimation of best straight line presents doubts about the reliability of the observations corresponding to quenching temperatures (306 and 633°K). Since the author is confident about the observations presented here, it is likely that these unusual observations may be due to some unknown factor(s) operating in the physical processes of InSb or inadequacy of the empirical formulae for hardness used in the present work or conceptual and theoretical deficiencies about hardness.

A.5 CONCLUSIONS

(i) The defect structures operate differently in low and high load regions.

(ii) Hardness depends upon quenching temperatures. Relations between hardness and quenching temperature in the high load region is given by

(a) $H\,T_Q^{k}$ = Constant, where k = -0.11 for InSb crystal

(b) $a_2\,T_Q^{r}$ = Constant, where r = - 0.08 for InSb crystal

(c) $a_2\,H^{s}$ = Constant, where s = - 0.779 for InSb crystal.

(iii) The above conclusions are in general agreement with those obtained for single crystals of KCl, KBr, $CaCO_3$, $NaNO_3$, Zn and TGS.

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