CHAPTER 5
MICROHARDNESS STUDIES OF SbSI AND SbSeI CRYSTALS
5.1 THE CONCEPT OF HARDNESS

The concept of hardness developed by everyone, whether layman or scientist is peculiar to their own sphere of activity. In the home the hardness of materials is thought in terms of the readiness with which they can be cut with the kitchen knife. In the workshop hardness is judged by the fitter by the ease with which a given material can be sawn, filed or drilled. The materials are often graded by the engineer on the basis of the depth of penetration of a hard indenter when forced into the surface under controlled conditions and is also interested in the resistance to abrasion under working conditions. We know that the harder of the two materials will scratch the other, will resist wear better or suffer less damage if struck by a body which is harder than either material. On reflection we realize how varied are the properties loosely referred to as hardness, many of them unconnected and bearing little relation to each other [1].

The definition of hardness depends entirely on the method of measurement which will determine the scale of hardness obtained. Following the suggestion by Ashby [2], probably the best general definition that can be given is that 'hardness is a measure of the resistance to permanent deformation or damage'. Method of measuring hardness is not dependent on a single physical property but may involve both the elastic and plastic deformation characteristics of the material so that the elastic limit, elastic modulus,
yield point, tensile strength, brittleness etc., all play a part in the result obtained. Further, it is important to realize that the 'hardness' properties of the material may change appreciably as the test is applied. For example in an indentation type of test, the initial penetration of the indenter increases the resistance of the material to further indentation so that the best we can do is to determine the resistance of the material to penetration when indented by a certain load [1].

Indentation type is the most commonly used form of test and the hardness value obtained is the one which the engineer is most interested. In this test a hard indenter of specific shape is forced into the material under standard conditions and the permanent impression produced is measured.

5.2 HARDNESS TESTING METHODS

The different methods of hardness testing classified by Mott [1] are as follows:

1 Static indentation test: A steady load is applied to an indenter which may be a ball, diamond cone or diamond pyramid and the hardness is calculated from the area or depth of indentation produced. This is the most important type of hardness test. It covers a wide range of testing conditions. The main variants are the nature of the indenter and the load applied. Naturally, since it is required to test materials covering a wide range of hardness, the indenter is made from a very hard material to prevent its deformation by the test piece. For this reason either a hardened steel sphere or a diamond pyramid or cone is employed. A pyramid also has the advantage that geometrically
similar impressions are obtained at different loads. So naturally a pyramid indenter is preferred.

2 Dynamic indentation test: A ball, cone or a number of small spheres is allowed to fall from a definite height and the hardness number is obtained from the dimensions of the indentation and the energy of impact.

3 Scratch test: This can be subdivided into two types: (a) comparison test in which one material is said to be harder than another if the second material is scratched by the first; (b) a scratch is made with a diamond or steel indenter traversing the surface at a steady rate and under a definite load. The hardness number is expressed in terms of the width or depth of the groove formed.

4 Rebound test: The hardness is given by the height of rebound of a diamond tipped weight falling on the surface from a fixed height.

5 Pendulum recoil test: A jewel or steel ball is attached to a pendulum which is made to swing; the amplitude of the first swing or the time of oscillation of a number of swings is taken as a measure of hardness.

6 Abrasion or machinability test: Various types of mechanical tests to measure the resistance to wear when subjected to a sliding or rotary motion or to various cutting operations.

5.3 FORMULAE RELATING TO INDENTATION HARDNESS TESTING

The general definition of indentation hardness which relates to the various forms of indenter is the ratio of the
load applied to the surface area of the indentation. On this basis, hardness has the dimensions of a pressure, \( \text{ML}^{-1} \text{T}^{-2} \).

For Brinell testing \([3]\), if the load on the ball is \( P \) kg, the diameter of the ball \( D \) mm and the measured diameter of the impression of the load removed is \( d \) mm, then since \( H_B = \text{Load/curved area of impression} \), it can easily be shown that \([1]\)

\[
H_B = \frac{L}{\frac{1}{2} \pi D \left( D - \sqrt{D^2 - d^2} \right)} \text{kg/mm}^2 \tag{5.1}
\]

If the load on the given sized ball is increased, then the depth of penetration into a given material becomes greater. Hence the angle of indentation made with the surface changes. The conditions are then different for shallow and deep impressions. For this and other reasons, \( H_B \) varies with the load for a given ball diameter and with the ball diameter for a given load. Thus if the diameter of the ball is changed, then to preserve geometrical similarity, the load should also be changed to maintain a constant value of \( L/D^2 \).

Meyer \([4]\) has found experimentally that for a given diameter of ball, as the load is varied the following relationship holds;

\[
P = a d^n \tag{5.2}
\]

where \( a \) and \( n \) are constants for a given material. Further, \( n \) varies from about 2.0 to 2.5 depending on the condition of the material. It has the higher value for the fully softened state and decreases with the degree of cold work given to the specimen. The value of \( n \) can therefore be considered as
representing the capacity for workhardening and may be determined experimentally by making tests at various loads. Since we have

\[ \log P = \log a + n \log d \]  \hspace{1cm} (5.3)

where \( n \) is the slope of the line obtained by plotting the values of \( \log d \) against \( \log P \). This test has become known as a 'Meyer analysis' for a given material.

Meyer [4] has also proposed that hardness should be defined as the ratio of the load to the projected area of the indentation when

\[ H_M = \text{Meyer hardness} = \frac{P}{\pi \left( \frac{1}{2} d \right)^2} = \frac{4P}{\pi d^2} \]  \hspace{1cm} (5.4)

In the Vickers hardness test, a square-based pyramid is used for which the angle included between opposite faces is ideally 136°. From the general definition of hardness, for a given diagonal \( d \) mm we have

\[ \text{Vickers hardness number} = \frac{2P \sin \alpha / 2}{d^2} \]

or \[ H_V = \frac{2P \sin 68^\circ}{d^2} = 1.8544 \frac{P}{d^2} \]  \hspace{1cm} (5.5)

Contrary to the conditions relating to the Brinell test, the geometry of the indentation made with the Vickers pyramid is independent of the depth and hence of the load so that on these grounds, the hardness should be independent of the load [1].
Spaeth [5] has suggested that hardness should not be defined as a stress but as the resistance to indentation in the form of the ratio of the specific surface load to the unrecovered deformation, i.e., of the load to the volume of material removed. On Spaeth's definition therefore, the hardness number is equivalent to the hardness as given by the Vickers, Brinell or Knoop tests divided by the depth of impression. Spaeth considers that the reciprocal of this hardness number can be taken as a measure of 'softness'.

Referring back to Meyer's law discussed earlier, we have

\[ P = a d^n \] (5.2)

where \( a \) and \( n \) are two constants depending on the material. If we combine this with the hardness equation

\[ H = KP / d^2 \] (5.6)

where \( K \) is a constant depending on the indenter, then we have

\[ H = K a d^{n-2} \text{ or } K a^{2/n} P^{(n-2)/n} \] (5.7)

These expressions indicate that unless \( n = 2 \), the hardness depends upon the size of the impression or the load employed in the test. Grodzinski [6] prefers to define the hardness as

\[ h = P / d^n = a \] (5.8)

This shows that a hardness \( h \) is obtained as the load for 'unit deformation', and is a constant which can be deduced...
experimentally by carrying out Meyer analysis. Grodzinski [6] has suggested therefore that the hardness \( h \) can be defined as the load in kg or grammes which produces an indentation diagonal of unit length of say 0.1 cm, or 0.01 cm and so on. As defined, \( h \) is a function of the load \( P \), the diameter or diagonal \( d \) and the index \( n \), whereas from the accepted formula, hardness \( H \) is independent of \( n \) [1].

5.4 RELATION BETWEEN HARDNESS AND OTHER PHYSICAL PROPERTIES

Basically, the hardness properties are obviously related to the crystal structure of the material or, in other words, to the way the atoms are packed and the electronic factors operating to make the structure stable. Schwab [7] has drawn attention to the relationship of the Brinell hardness and its temperature coefficient in the Hume-Rothery phases of the alloy systems Cu-Zn, Cu-Sn, Ag-Zn and Ag-Cd with the Brillouin zones of these compounds. He considers that if the first zone is full, then the energy required to move a dislocation through the lattice is greater than if the zone is incompletely filled and hence the hardness is higher. The extreme hardness of diamond can be related to its highly stable covalent structure [1].

Richer [8] has attempted to give a physical interpretation of indentation hardness on the basis of the stress/strain relationship obtained in a tensile test. He considers that when an indenter is loaded and penetrates a material, the depth of penetration increases until the condition of the lattice immediately below the indenter has the same characteristics as that of a specimen in which the saturation
value of compressive strain has been attained. Holm et al [9] have discussed the relationship between hardness and the yield point and on this basis are able to compare the Brinell and Rockwell hardness numbers for a given material. Their [9] experimental work indicates that the hardness is approximately equal to three times the yield stress provided certain conditions of work hardening capacity and geometry of the impression are satisfied. Tabor [10-12] has developed this theory further and considered the effect of the work hardening capacity on the ratio of \( H_p \) to yield stress and the relationship between the \( H_v \) and maximum tensile stress for a number of materials. Meyer [13] has also related the hardness numbers obtained in indentation tests with balls, pyramids and cones with the plastic and work hardening properties of the material.

Cardullo [14] concludes that hardness is a function of both the modulus of elasticity and the elastic limit of a material and expresses the hardness number as

\[
H = c E^m P^n
\]

(5.9)

where \( c \) is a constant, \( E \) the modulus of elasticity, \( P \) the elastic limit in compression and \( m \) and \( n \) are small positive indices which Cardullo considers to be near unity. Arbtin et al [15] have investigated the \( H_v \) of a number of metals, the moduli of elasticity of which fall into three main ranges. Their results show no apparent relationship between the yield strength and the hardness.

In view of the dependence of the measured pyramid hardness number with load which has been reported by various workers, Braun [16,17] has attempted to express the hardness in terms of the stress/strain curve, taking into account
both the elastic and plastic properties. He distinguishes between a fully annealed metal and one which has been cold worked to give a permanent strain and introduces the conception that there is a relationship between the hardness and the extension to fracture, the latter being determined by the degree of cold work.

According to Stillwell [18], the hardness of a solid is defined by the resistance against lattice destruction and is considered to be a function of interatomic forces. All hardness measurements are relative, and the data obtained by the many different methods of hardness testing are for the greater part not comparable with one another [19]. Hardness has in general defined unambiguous physical definition. The lattice energy data from infrared spectra combined with a study on lattice anharmonicity form a basis for an examination of hardness from the atomic aspect [20]. In technical hardness testing, hardness can be defined by a pressure or force per square centimetre (kg/cm\(^2\)) and thus be conceived as an energy per volume (kg cm/cm\(^3\)), e.g., the ratio between input energy and scrapped volume. Proceeding now to the atomic aspect we should likewise know the dimension of an energy per volume for the resistance of the lattice against destruction during hardness testing. Thus we examine this resistance as a function of "the lattice energy per unit volume" and call it "volumetric lattice energy" having the dimension (Kcal/cm\(^2\)) [20]. The volumetric lattice energy is given by the ratio between the total cohesive energy of the lattice (lattice energy) per mole and the mole volume. An unambiguous linear relationship between both hardness and volumetric lattice energy is established for the entire hardness range of solids. The mechanical properties of solids appear to be controlled by the amount of anharmonicity of the
respective cohesive forces. If the related mass values of adjacent atoms or ion partners decrease substantially below unity, a strong increase of mutual interpenetration or interlinking of the atoms occurs with a corresponding increase of the lattice anharmonicity. This results in a very strong resistance against lattice destruction or a very high hardness value [20]. Selective hardness properties (anisotropy) generally result from differences between the cohesive forces in various crystallographic directions, since the lattice energy values integrate these forces. Recently, Kishan Rao et al [21] have correlated the Vickers microhardness values with the strength of interatomic binding of some cubic crystals. According to them shorter the interatomic distances, stronger is the binding and hence greater is the hardness value.

5.5 APPLICATION OF MICROHARDNESS TESTING

Hardness testing is very widely used for classifying materials mainly because of the ease with which it is accomplished. Primarily it is a non-destructive test and can be used for determining the suitability of a material for a given purpose. The success of a given method of fabrication or heat treatment can easily be assessed and at the same time the uniformity of the product may be checked. Microhardness studies find wide applications in the study of mechanical properties of solids. Microhardness also correlates with other mechanical properties like elastic constants [22] and yield stress of solids [23]. There is also possibility of investigating various properties by means of microhardness measurements [24]. Although the mechanism of deformation during indentation is not clearly understood, microhardness testing provides useful information concerning
the mechanical behaviour of brittle solids. The indentation techniques have been used by many investigators [10, 25, 26] to study glide, deformation anisotropy, cracks, grain boundary hardening, state of dispersion of the impurity, quench hardening, irradiation and environment of dislocation mobility of various crystals. Microhardness measurements have also been used in the study of grain boundary properties.

5.6 MICROHARDNESS STUDIES OF SbSI AND SbSeI CRYSTALS

5.6.1 Introduction

From literature one can note that no important data concerning the mechanical properties of SbSI and SbSeI have been reported. It may also be mentioned that practically no study has so far been made on microhardness of these materials. Having undertaken investigation on the mechanical properties of these materials, the author presents, in this chapter, the results of indentation-induced hardness testing studies on SbSI and SbSeI crystals. Hardness studies have been carried out for (100) face of the respective single crystalline platelets as well as for the ingot surfaces [(001) face of the needle crystals]. From this study Kick's [27] analysis on hardness as well as Hays and Kendall's law [28] have been verified. Vickers microhardness test has been employed for these purposes. The values of \( n \), the work-hardening exponent are also computed using the least-squares fit method for different load regions and the results are discussed.
5.6.2 Vickers microhardness test

All hardness measurements are relative, and the data obtained by the many different methods of hardness testing are for the greater part not comparable with one another [19]. With the introduction of diamond pyramid indenters, hardness testing has been widely used to study the strength and deformation characteristics of materials [1]. The behaviour of indentation hardness at low load has been a controversial subject and one widely discussed [24, 29, 30]. Among the various types of hardness measurements, the most common and reliable type is the Vicker's hardness test. In this test, microindentation is made on the surface of the crystal with the help of a diamond pyramid indenter. The Vickers pyramid indenter whose opposite faces contain an angle \( \alpha = 136^\circ \) is the most widely accepted pyramid indenter. Pyramid indenters are said to be best suited for hardness test due to two reasons [31] namely:

1) The constant pressure for a pyramid indenter is independent of indent size; and

2) Pyramid indenters are less affected by elastic release than other indenters.

The base of the Vickers pyramid is a square and the depth of indentation corresponds to 1/7th of the indentation diagonal. If Vickers diamond pyramidal indenter tip is undamaged, it can be used to make very small indentations, still retaining the characteristic shape for measurements. It is used not only for crystals but also for metals, ores, glass and ceramic parts, electroplating and industrial products. For reliable measurements of hardness of very soft to very hard single crystals microindentation hardness test is preferred,
because very small load gives more accurate microhardness values.

5.6.3 Refinement of microhardness test

Many investigators [32,33] have also refined the microindentation method by etching the crystal after indenting and measuring the diameter of the dislocation array around the indentation. This technique has not only yielded greater sensitivity but also given some indication of the nature of the plastic flow around the indentation. Many workers [34-39] have described how to improve the strength (hardening of the crystals) by doping with impurities, quenching from high temperature and irradiations. The role of hardening mechanism of such processes has also been studied by them using microindentation followed by etching of such materials.

5.6.4 Experimental

SbSI and SbSeI single crystalline platelets and ingots grown from the melt by Bridgman technique are used for hardness studies. It is very difficult to obtain cleaved surfaces of these crystals and so plane surfaces, microscopically free from sign of any damage are chosen for the indentation purposes. The dimension of the platelets used are 10 x 2 x 0.25 mm$^3$. In the case of the ingots, they are embedded in a resin and slices are cut perpendicular to the ingot axis in order to get (001) faces of the needles forming the ingot. From these slices convenient test samples with (001) faces are obtained. The cuts are polished and rinsed with methyl alcohol and dried to remove the work hardened surface.
Indentations are made with a Leitz microhardness tester (Figure 5.1). The diagonals of the impressions are measured using a Leitz Metallux II microscope with a calibrated ocular at magnification x 500. The measurements are made at room temperature and the indentation time is kept at 15 seconds. Microhardness is measured on the (100) face of the single crystalline platelets as well as on the ingot surface [(001) faces of the needles] of SbSI and SbSeI crystals in the low-load region (2 to 50 g). For hardness determination, the crystals are indented at different sites so that the distance between the two indentations are more than 3 times the diagonal length. This is done to avoid any mutual influence of the indentations. Diagonal lengths, d of the indented impressions obtained for various loads are measured using the micrometer eye-piece. As much as fifteen indentations are made for a constant load in all the cases. The microhardness value is taken as the average of the several impressions made with both diagonals being measured. Hardness of the crystal is calculated using the relation

\[ H_v = 1.8544 \frac{P}{d^2} \text{ kg mm}^{-2} \] (5.5)

where \( H_v \) is the Vickers hardness number, \( P \) is the indenter load in grams and \( d \) is the diagonal length of the impression in \( \mu \text{m} \).

5.6.5 Results

The deviation in hardness values for each sample at each load in various trials is less than ± 3 kg mm\(^{-2}\). Figures 5.2 and 5.3 show the impression of the indentations made on SbSeI platelet [(100) face] as well as SbSeI ingot
Fig. 5.1 Leitz microhardness tester
Fig. 5.2 Indentations made on SbSeI platelet
a. indentation for 2 g x 700
b. indentation for 5 g x 500
c. indentation for 10 g x 460
d. indentation for 25 g x 360
e. indentation for 50 g x 490
Fig. 5.3  Indentations made on SbSeI ingot

a. indentation for 2 g x 800
b. indentation for 5 g x 740
c. indentation for 10 g x 400
d. indentation for 25 g x 490
e. indentation for 50 g x 400
[(001) face of the needles] at different loads, 2, 5, 10, 25 and 50 g respectively. It is clearly observed from Figures 5.2 and 5.3 that the size of the impression increases with the load. This is also found in the case of SbSI platelet as well as SbSI ingot (not shown in figure).

Plots of Vickers hardness against load are drawn for SbSI as well as SbSeI crystals studied (Figure 5.4). From this figure one can see that there is a variation in the value of microhardness as load varies. Though the variation is not the same for these two materials, the value of microhardness decreases as the load increases for both the materials. It is significant to note that there is a rapid fall in the value of microhardness until a load of 10 g is reached and thereafter there is a tendency to attain saturation. In this respect, all the curves belonging to SbSI and SbSeI crystals show a striking similarity between loads of 10 and 50 g. These curves show that the variation of microhardness with load is not linear. This is very significant in the light of the discussion which follows.

5.6.6 Discussion

The results obtained from Figure 5.4 show that as the applied load decreases, the hardness of the materials increases, whether they are SbSI or SbSeI. The variation is not linear for these materials and are not in accordance with what is suggested by Kick [27]. The variation in the Vickers microhardness number with load has been studied widely on a large number of materials. However, some of the reported results indicate that the microhardness of a given material is constant above a critical size of penetration of the indenter impression, but below this size an increase
Fig. 5.4 Variation of microhardness with load.

- O SbSI Plate
- △ SbSeI Plate
- ● SbSI Ingot
- ▲ SbSeI Ingot

\[ H_v (\text{Kg mm}^{-2}) \]

\[ P (10^{-3} \text{Kg}) \]
in microhardness occurs as the load is decreased [1,30, 40-42]. Gane et al [24] have put forward an alternative explanation suggesting that the increase in microhardness at small indentation size is due to an increase in the stress necessary to operate dislocation sources in a perfect crystal region. The size of the dislocation of the rosette produced around microindentation is an useful and convenient test for determination of mechanical strength of the crystals. Palaniswamy [43] has investigated the indenter impression at various applied load on Li$_2$CO$_3$ crystals and subsequently etched. He has found that the mobility of dislocation lines around the indentation mark increase with the applied load, suggesting that the microhardness decreases with increase in applied load. Similar observations have been reported by Pratap et al [32] and Kotru et al [33]. Upit et al [44] have obtained results on alkali halide crystals which they interpret as due to the effect of the surface on the mechanical properties of the bulk crystal.

Kick [27] has proposed an analysis of results on hardness and according to him the relation between applied load $P$ and indentation length $d$ is presented by

$$P = K_1 d^n$$ (5.10)

where $K_1$ and $n$ are constants for a given material. In his analysis for hardness, Kick postulated a constant value of $n = 2$ for all the indenters and for all geometrically similar impressions. This equation is further supported by Schultze et al [45] who have proposed that Vickers microhardness and macrohardness values are comparable. However, Kick's law has not received wide acceptance on account of the fact that $n$ usually has a value less than 2, particularly in the low load region. If $n$ is less than 2, the
hardness number increases with decreasing load, and if \( n \) is greater than 2, it decreases with decreasing load [46]. In the present study [47-49] \( n \) is found to be less than 2 (Figure 5.5) and the hardness number is found to increase with decreasing load (Figure 5.4) in all the cases. Hays et al [28] have attempted to overcome this difficulty by assuming that a resistance to deformation could be evaluated by considering it as a Newtonian resistance pressure of the specimen itself. As load \( P \) is applied to a crystal sample, they assume that the load \( P \) is partially affected by a smaller resistance pressure \( W \) which is a function of the material under testing. According to them, \( W \) represents the minimum applied load needed to produce an indentation, since the load \( W \) allows no plastic deformation.

Considering the sample resistance pressure, the equation given by Kick is modified as

\[
P - W = K_2 d^2 \tag{5.11}
\]

where \( K_2 \) is constant and \( n = 2 \) is the logarithmic index. Since the factor \( W \) allows the limiting case to prevail where microhardness is not marked by dependence on the load, \( n \) should turn out to be equal to 2. To evaluate the fraction \( W \) by solving above equations, one gets

\[
W = K_1 d^n - K_2 d^2 \tag{5.12}
\]

From this

\[
d^n = W/K_1 * (K_2/K_1) d^2 \tag{5.13}
\]

It is now possible to apply these equations by ordinary
Fig. 5.5 Log P against Log d plot
graphical methods. A logarithmic form of Kick's equation indicates that if log $P$ is plotted against log $d$, we are in a position to obtain slope $n$ and the intercept log $K_1$ (from which $K_1$ can be calculated). Figure 5.5 represents the dependence of log $P$ on log $d$ for the data obtained in the present work. The values of $K_1$ and $n$ as obtained from Figure 5.5 are recorded in Table 5.1 for SbSI and SbSeI. From these calculations one finds that $n < 2$ in all the cases of the present work.

A cartesian plot of Equation 5.13 suggests that if $d^n$ is plotted against $d^2$, it should yield the slope $K_2/K_1$ and the intercept $W/K_1$. Having already determined $K_1$ from the logarithmic plot of $P$ and $d$, one can obtain the values of $K_2$ and $W$. A graph of $d^n$ against $d^2$ yields a straight line in all the cases of the present work. Figures 5.6 and 5.7 show the graph of $d^n$ against $d^2$ for SbSI and SbSeI respectively. The values of $W/K_1$ (intercept) and $K_2/K_1$ (slope) as obtained from these curves are given in Table 5.1 for the materials under investigation. Knowing $K_1$ the value of $W$ is found out by substituting the value of $K_1$ in $W/K_1$ and $K_2$ is found out by substituting the value of $K_1$ in $K_2/K_1$. The values of $W$ and $K_2$ are also given in Table 5.1.

Figure 5.8 is the graph in which the logarithm of true applied load ($P-W$), i.e., log ($P-W$) is plotted against the logarithm of the Vickers diagonal, i.e., log $d$ (from the data obtained in the case of materials under investigation). From these graphs, $n$ is found to be equal to 2 in all cases [49], in accordance with the assumption of resistance pressure of the crystal specimen as proposed by Hays et al [28]. This applicability is also found true for rare earth pervoskites (orthoferrites, orthochromites and aluminates).
Fig. 5-6 $d^n$ against $d^2$ plot of SbSI
Fig. 5.7 $d^n$ against $d^2$ plot of SbSeI
Table 5.1 Values of $K_r$, $n$, $W/K_1$, $K_2/K_1$, $W$ and $K_2$ for SbSI and SbSel

<table>
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<th>Specimen</th>
<th>$K_r$ $10^{-3}$ kg</th>
<th>$n$</th>
<th>$W/K_1$</th>
<th>$K_2/K_1$</th>
<th>$W$ $10^{-3}$ kg</th>
<th>$K_2$ $10^{-3}$ kg</th>
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<tr>
<td>SbSI plate</td>
<td>0.09332</td>
<td>1.772</td>
<td>13.50</td>
<td>0.4614</td>
<td>1.259</td>
<td>0.04306</td>
</tr>
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<td>SbSI ingot</td>
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<td>22.25</td>
<td>0.5520</td>
<td>1.141</td>
<td>0.02831</td>
</tr>
<tr>
<td>SbSel plate</td>
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<td>16.00</td>
<td>0.5505</td>
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<td>0.03680</td>
</tr>
<tr>
<td>SbSel ingot</td>
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<td>1.916</td>
<td>24.00</td>
<td>0.7174</td>
<td>0.576</td>
<td>0.01719</td>
</tr>
</tbody>
</table>
Fig. 5.8 log (P-W) against log d plot
### Table 5.2 Work-hardening exponent $n$ for different load ranges

<table>
<thead>
<tr>
<th>Specimen</th>
<th>n for different load ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-10 g</td>
</tr>
<tr>
<td>(100) face of SbSeI platelet</td>
<td>1.8643</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>SbSeI ingot surface</td>
<td>1.4657</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>SbSI ingot surface</td>
<td>1.4326</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
by Kotru et al [33], alkali halide crystals by Pratap et al [32] and \( \text{Li}_2\text{CO}_3 \) single crystals by Palaniswamy [43]. It is thus concluded that SbSI and SbSeI fall in the class of materials to which the idea of resistance pressure as proposed by Hays et al [28] is applicable [49].

The values of \( n \) are computed using the least-squares fit method for different load regions and given in Table 5.2. The work-hardening exponent is higher when the indenter load is increased [47,48].

5.6.7 Conclusion

1. Vickers hardness decreases with increase in load for SbSI as well as for SbSeI crystals. The variation is also non-linear with load (Figure 5.4) [47,48].

2. To check the validity of the Kick's relation, a logarithmic plot of \( P \) and \( d \) is drawn (Figure 5.5), which yields value of \( n \) less than 2 for both the crystals [47,48].

3. The idea of resistance pressure as proposed by Hays et al [28] is found to be true from the hardness studies made on SbSI and SbSeI crystals (Figure 5.8) [49].
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[30] H. Buckle, 'Progress in microindentation hardness test-


