Textural and Magnetic Properties of Cross-Rolled Silicon Steels

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

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METALLURGICAL AND MATERIALS ENGINEERING

By

AMAR JASPRIT DUNGDUNG (110MM0352)

RAKESH KUMAR SETHY (110MM0382)

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA

National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled, " **Textural and Magnetic properties of Cross-rolled silicon steels”** submitted by **Amar Jasprit Dungdung (110MM0352)** and **Rakesh Kumar Sethy**(**110MM0382**) in partial fulfillment of the requirements for the award of **Bachelor of Technology Degree** in **Metallurgical and Materials Engineering** at National Institute of Technology, Rourkela is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date:

Prof. Santosh Kumar Sahoo
Dept. of Metallurgical and Materials Engineering
National Institute of Technology
Rourkela-769008

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Place: NIT Rourkela

Amar Jasprit Dungdung(110MM0352)

Rakesh Kumar Sethy (110MM0382)

ABSTRACT

Silicon steels are widely used for their electrical applications in motors, generators, small transformer cores due to their high permeability, low core losses and their uniform magnetic properties in all directions of the material. The major processing steps involved for the production of silicon steels are hot rolling, cold rolling and annealing. The processing steps largely affect the texture of these steels which subsequently improves the electrical properties of these steels. The objective of the present study is to investigate the cross-rolling effect on texture development of silicon steels and its magnetic/electrical properties. X- ray Diffraction (XRD) method is carried out on the sample to understand the textural development. PC based Pulse Field Hysteresis Loop Tester is used to estimate the magnetic properties. It is observed that the steels have improved textural and magnetic properties.

Keywords: Silicon steel, texture, magnetic permeability, core loss.

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CHAPTER 1

INTRODUCTION

1.0 BACKGROUND

Silicon steel or Electrical steel was developed at the beginning of the 20th century and soon was widely used as the preferred core material for large transformers, motors, and generators. Silicon-bearing steels are used as soft magnetic materials in electrical appliances and devices and are rated in terms of power loss when magnetized in an alternating electric field.

Two important metallurgical factors that are responsible for the above said properties are grain size and texture [1]. As grain size increases, hysteresis loss decreases due to increase in domain width, and eddy current loss decreases [2]. So, there is an optimum grain size which determines the sum of hysteresis loss and eddy current loss to a minimum value. The existence of an optimum grain size can be explained from domain theory, which can be demonstrated as, below the optimum grain size hysteresis loss due to domain wall interactions is predominant while above the optimum grain size losses are linked to domain wall movement.

Texture is one of the most important parameters determining the magnetic properties of steel sheets. The ideal texture of non-oriented silicon steel sheets would be a cubic texture with grains with their (001) or (110) planes parallel to the plane of the sheet and a uniform distribution of the [100] direction, whereas the Goss texture with a (110)[100] crystallographic orientation of the grains is the typical grain structure of grain-oriented silicon steel.[3]. Material with a texture favorable for magnetic properties shows lower core loss than those with an unfavorable texture, although they may have same grain size [4]. Thus, (001)<uvw> texture component is the most desirable while (110)<uvw> is the most preferable and (111)<uvw> is the most avoidable texture component in a Silicon steel[5]. So it is very important to link between the metallurgical factors and magnetic properties before producing certain equipment [6]. The texture of the silicon steel is controlled by subjecting the sample to hot rolling then cold rolling followed by annealing.

1.1 OBJECTIVES

- Study the variation in texture of cross-rolled silicon steel with respect to angular direction, i.e., 1) rolling direction 2) 45° to the rolling direction 3) transverse direction.
- Determination of magnetic properties like core loss and permeability of the cross rolled Silicon steel sample.

Chapter 2:

LITERATURE REVIEW

2.1 SILICON STEELS

It is one of the most strategic magnetic materials produced today. Silicon steel or Electrical Steels are essential in the fabrication of a number of electrical equipment such as transformer cores and are a preferred core material for equipments like motors and generators [7].

The properties of these steels are:

1. High permeability
2. High magnetic induction
3. Low magnetic losses
4. Low magnetostriction

High permeability and induction effectively reduces the weight and size of the parts leading to the increase in efficiency, lowering the magnetic losses reduces the generation of core losses and subsequently the energy consumption, thus helping in the minimization of the energy and a low magnetostriction reduces the noise in the transformers and other high capacity machines by the production of less humming sound [8].

Importance of silicon

In late 19^{th} century when discovery of Si additions to increase the resistivity without affecting the saturation magnetization significantly electrical steel was developed. The addition of Silicon to iron has the following effects.

- The electrical resistivity is increased. Thus, the eddy currents and subsequent losses are lowered.

- There is an increase in permeability due to decrease in magneto crystalline anisotropy.
- Decrease in magnetostriciton.
- Reduction in the saturation induction.
- When the Si percentage is greater than 3% there is an increase in the brittleness of steel.

2.3 TYPES OF SILICON STEELS

There are generally 2 different types of Si steels.

- Grain oriented Silicon steel (GO)
- Grain non oriented Silicon steel. (GNO)

GO steels are the only class of material with 'complete' texture control through TMP, 'the product is characterized by a high magnetic moment approaching that of a single crystal, and the grains of the materials being substantially oriented at random throughout the structure. The characteristics crystallographic orientation obtained from TMP was named as Goss texture or {110}<001> preferred orientations.

GO steels primarily find application as core material for power and distribution transformers where a directional magnetic flux in desired. The Goss texture has <100> direction, which is the direction of easy magnetization parallel to rolling direction.

Although GO silicon steel has attracted more attention due to its properties, GNO steels are being the highest tonnage of electrical steels being produced today [9, 10]. Grain non-oriented silicon steel does not show a high Goss texture and thus, one of its main commercial use is in rotating electrical machinery in which the magnetic field is in the plane of the sheet, but the angle between the electric and magnetic field and the rolling direction continuously changes. Considering the case of rotating machineries' like motors, it is pointless to have a direction of easiest magnetization, i.e. <100>, parallel to the RD and an adequate texture would be {100}<uvw>, also known as <100> fiber texture [11]. The processing of GNO electrical steel comprises hot rolling which may be with annealing or without annealing followed by cold rolling in one or two steps with an intermediate annealing and later on undergo final annealing and coating. The GNO steel may be termed as Silicon steel i.e. cold rolled non-oriented steel and GO steel as

CRGO i.e. cold rolled grain oriented steel. Figure 2.1 shows the processing stages of non-oriented electrical steels

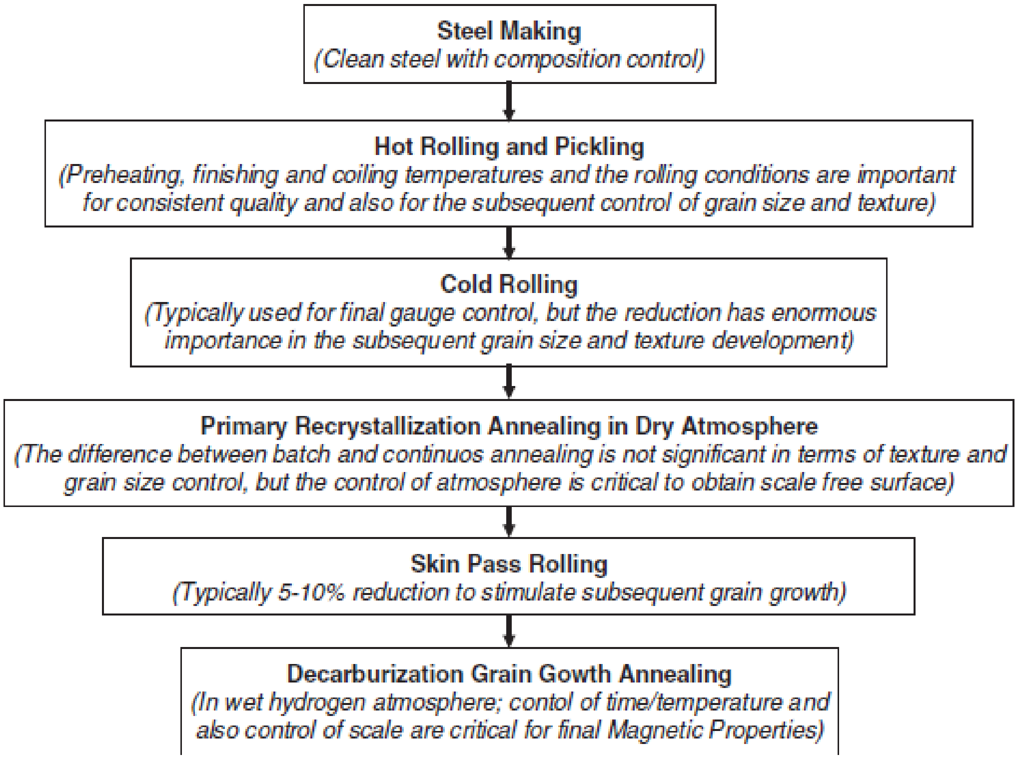


Fig 2.1 Typical processing stages of non-oriented electrical steel. The main issues involved in such steps are indicated. [12]

2.4 TEXURE

The magnetic property is dependent on the Orientation of grains/crystals is of silicon steels. Orientation of grains/crystals is also a deciding factor for determining the magnetic property of silicon steels. When the orientation of grains are statistically distributed at random, the material is said to be crystallographic isotropic and shows no preferred texture. However, if they are not randomly oriented, the material has a crystallographic texture. The term ‘crystallographic’ is used here only because the material can also show morphological texture as shown in Figure 2.2(c)[13].

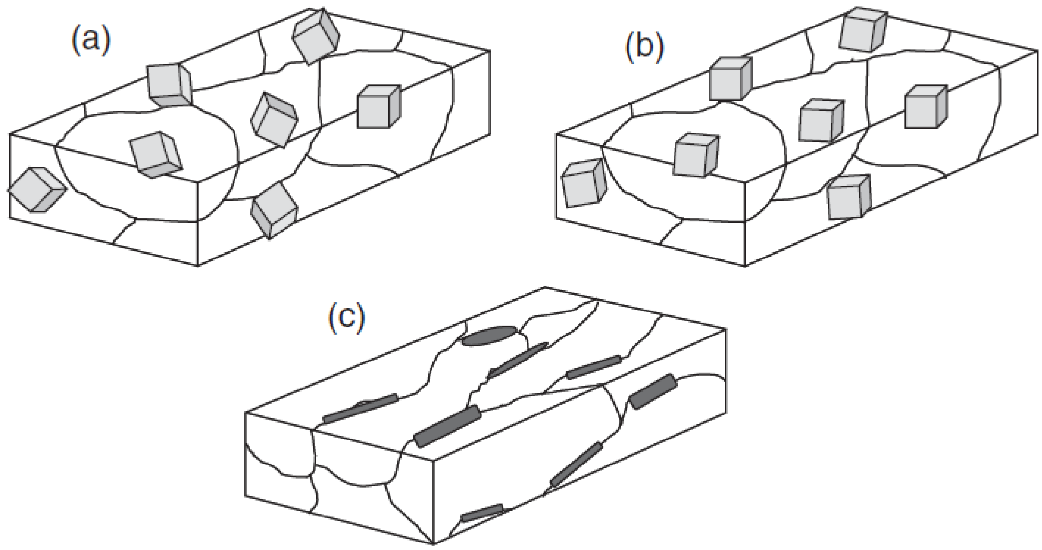


Fig 2.2 (a) material without texture, (b)a material with a crystallographic texture, (c) a material with morphological texture. The small cubes represent the crystallographic orientation of the grains.[13]

Crystallographic texture can be represented either by pole figure (PF) or orientation distribution function (ODF).

2.4.1. GRAIN ORIENTATION

It is very important for us to understand the concept of grain orientation and its representation before going into the concepts of PF and ODF. The orientation of a grain is always expressed relative to an external coordinate system. In flat products (plates, sheets), the external reference frame traditionally consists of the rolling direction (RD), the normal direction (ND) and the transverse direction (TD)[14]. Any crystal orientation can be expressed with the help of Miller indices and is written as: (hkl)[uvw]. This represents that the direction [uvw] is parallel with the RD and a plane (hkl) is parallel with the rolling plane. For example, the orientation of the crystal as in Figure 2.3 (a) should be written as (001)[1-10]. When all the crystallographic equivalent orientations are considered, the Miller indices are expressed as {hkl}<uvw>. In axisymmetric products (wires, extruded bars), one set of Miller indices [uvw] is used to describe the crystal orientation, indicating that this crystallographic direction is parallel with the sample axis, e.g. [111] in Figure2.3(b). All rotations around [uvw] are crystallographic equivalent [15].

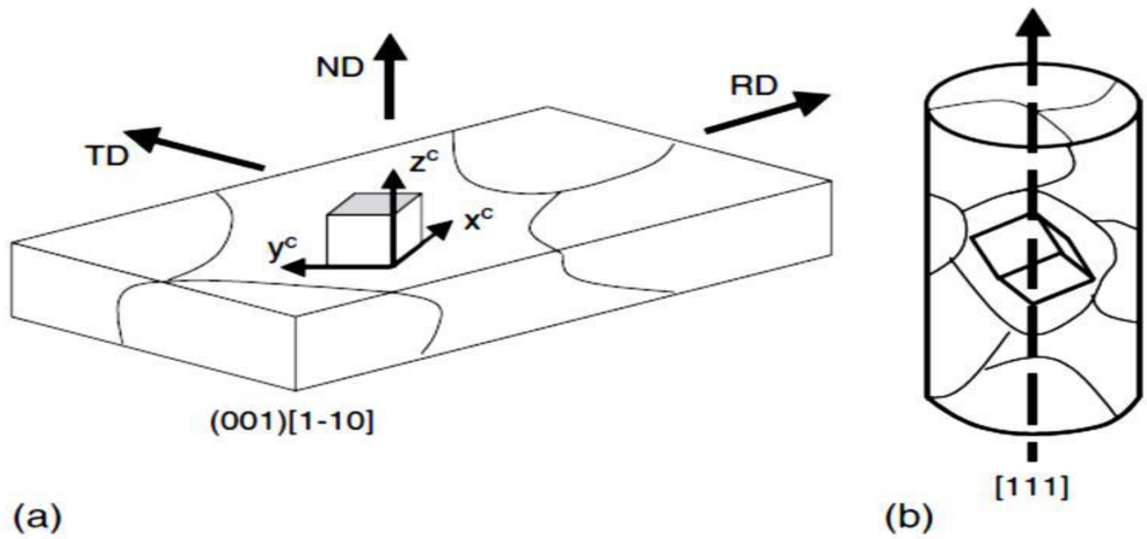


Fig 2.3 Examples of crystal orientations in sheet (a) and wire (b), expressed with Miller indices. The three cube axes are shown as x^c, y^c and z^c. [14]

2.4.2. POLE FIGURES:

Pole figures in the form of stereographic projections are used to represent the orientation distribution of crystallographic lattice planes in crystallography and texture analysis in materials science.[14]

Considering the polycrystalline specimen shown in Fig. 2.4, there are three grains. Each grain shows a definite orientation. In order to measure the {111} pole figure, we consider the distribution of directions normal to the {111} plane in each grain. This direction is also called {111} pole. As shown in Fig. 2.4, this {111} pole of each grain points into different directions represented by **P1**, **P2** and **P3** respectively. Each pole possesses its own coordinates in the sample reference frame. According to these polar coordinates, the poles are plotted as shown in Fig. 2.4(a). The stereographic projection thus obtained is called "pole figure". In actual situation, there will be millions of grains which are measured at one time and therefore many dots will appear on the pole figure. If the specimen is not textured the dots on the pole figure are distributed randomly and do not form any special pattern as shown in Fig. 2.4(b). Otherwise, a clustering of the different poles is observed as shown in Fig. 2.4 (c). Such pattern indicates that the specimen is textured.

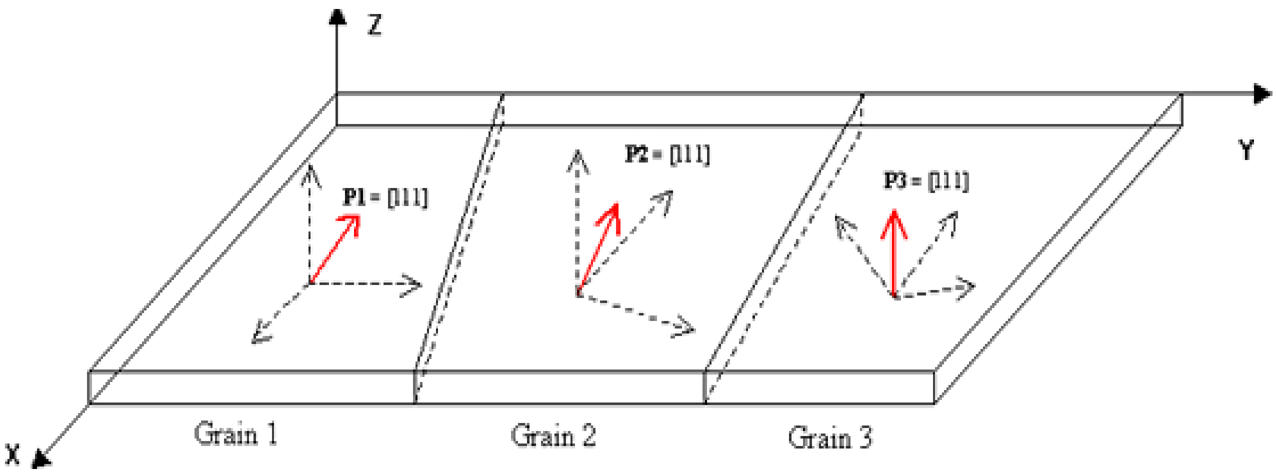


Fig 2.4: Polycrystalline specimen

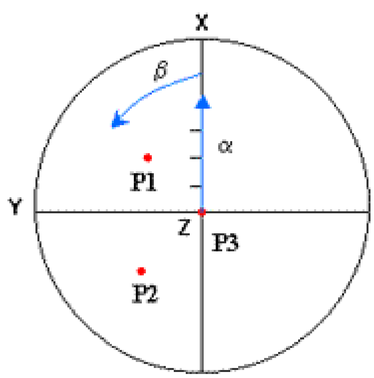


Fig 2.4 (a) Pole Figures

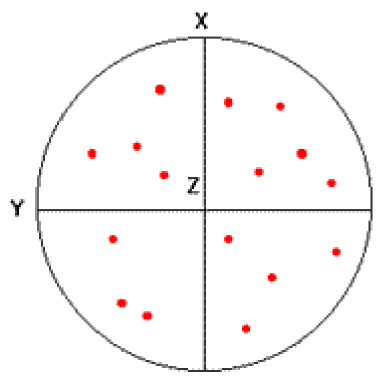


Fig 2.4 (b) Pole figure without texture

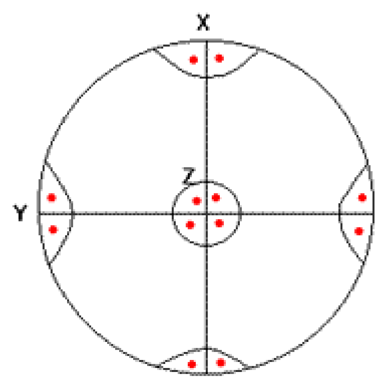


Fig 2.4(c) Pole figure with texture

2.4.3. ORIENTATION DISTRIBUTION FUNCTION (ODF)

Pole figure representation of texture accounted for several limitations. During projection of an orientation, certain orientations are missed as a 3D space is represented in a 2D circle. It is necessary to analyze all orientations for complete understanding of texture of the material. With the help of ODF, it is possible to describe the complete texture information of a sample [14].If the orientation of a grain can be represented by the parameter '*g*'. An ODF is a mathematical series expansion, for which we will use the symbol 'f' that describes the volume fraction of grains in all intervals $g \pm dg$.

$$(dV/V) = f(g).dg$$

The integral of the ODF over all orientations should sum up to 1. ODF is used statistically to make all possible orientation of grain where no loss of data occurs and measurement of sample gives accurate results. The ODF of a sample without any texture is a constant. If the sample possesses any texture, the ODF has maxima and minima [16].

2.4.4. EULER ANGLES:

In order to give a graphical representation of an ODF, a method must be found to define the orientation '*g'* of a grain. This is made possible by the concept of 'Euler angles'. In this concept two different co-ordinate systems are defined. The first is connected to the sample (sample axes system X_i) and the second to the crystal of a grain (crystal axes system). Both systems are Cartesian and right handed. Fig 2.5 shows the orientation of the crystal axis system and the sample axis system. The sample system is related to the shape of the sample. For example, for a rolled sheet, the axis X_1 is taken in the RD, X_2 in the transverse and X_3 in the ND of the sheet [14]. The orientation of the crystal axes system can now be expressed in the reference frame of the sample axes system by three rotations. These three rotations bring both systems together. In the literature, several conventions have been proposed to perform these rotations. The most widely used system is the system of Bunge where the rotation convention followed is ND-RD-ND. Figure 2.6 depicts the Bunge's method of rotation.

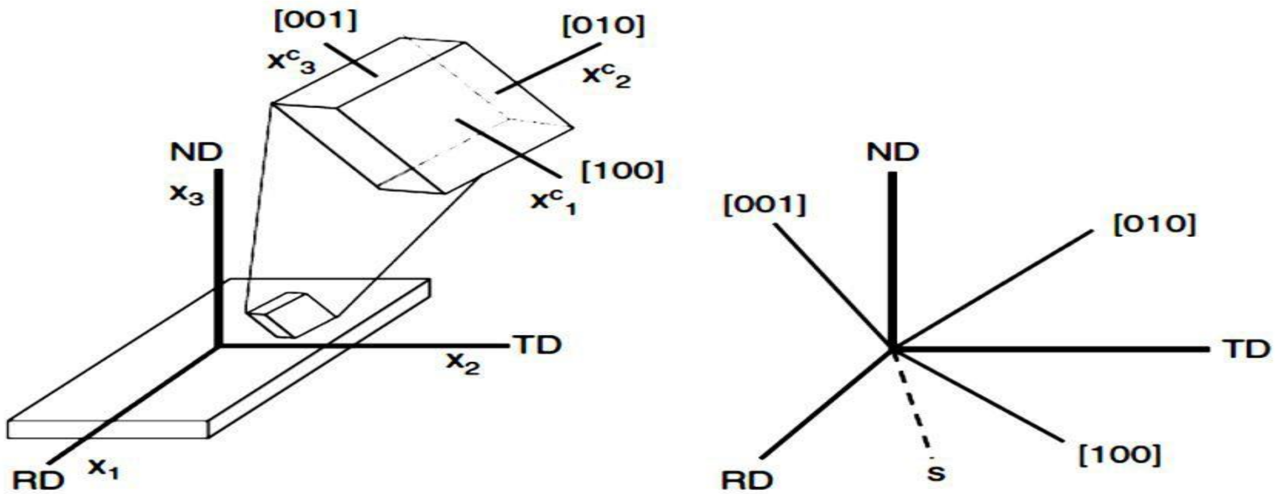


Fig 2.5 Orientation of the crystal axis system $\{X_i^c\}$ and the sample axis system {RD, TD, ND}; *s* is the intersection of the planes (RD–TD)and ([100]–[010])[17].

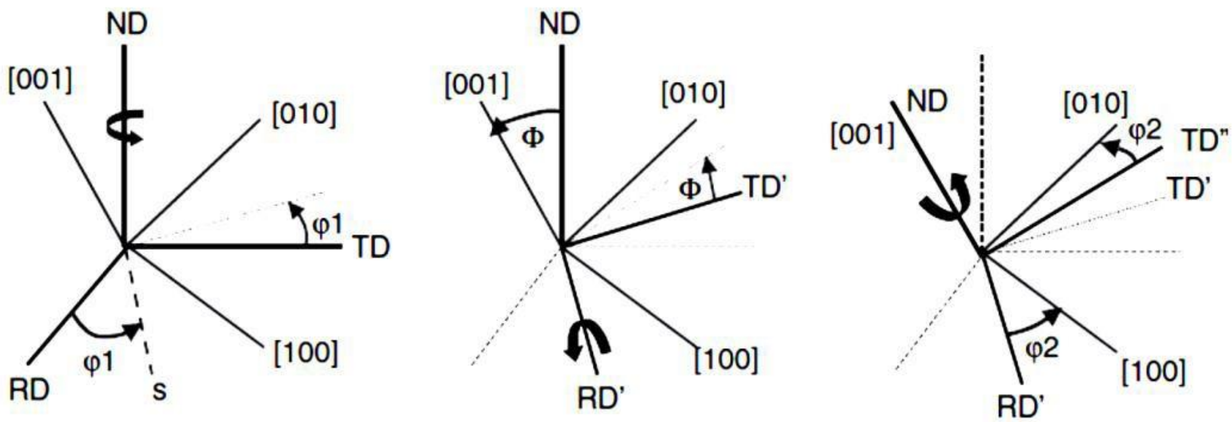


Fig 2.6 Definition of the Euler angles ϕ_1, Φ, and ϕ2 in the Bunge convention [18]

- .At first a rotation ϕ_1 around ND is performed; which will bring RD in the position*s*, with *s* the intersection of the planes (RD–TD) and ([100]–[010]). The attainment of new positions of RD and TD are now RD′ and TD′.
- Then, a rotation of Φ around RD′; this will bring ND together with[001];TD′ will now get the position TD′.
- Finally, a rotation of ϕ_2 around the ND axis(which is now equal to[001]);due to this rotation, RD′ falls on[100]and TD′ comes together with[010].The angles(ϕ_1, Φ, ϕ_2) are called ‘Euler angles’.

2.4.5. EULER SPACE

To represent every orientation in space it is important to represent it with the help of three Euler angles or 2 Euler angles by keeping the other one constant. When three Euler angles are used in 3D representation of texture data and when 2 Euler angles are used by keeping other being constant, it is called 2D representation of texture data which is normally used in real practice. When the three Euler angles are generally plotted in Cartesian coordinate system, we get the so called ‘Euler space’ [14]. This space is limited for φ1 and φ2 between 0° and 360°, and for φ between 0° and 180° (Figure 2.7). Each crystal orientation can be represented in this Euler space. In this representation, individual orientations will be found at several locations and at several Euler angles of the Euler space.

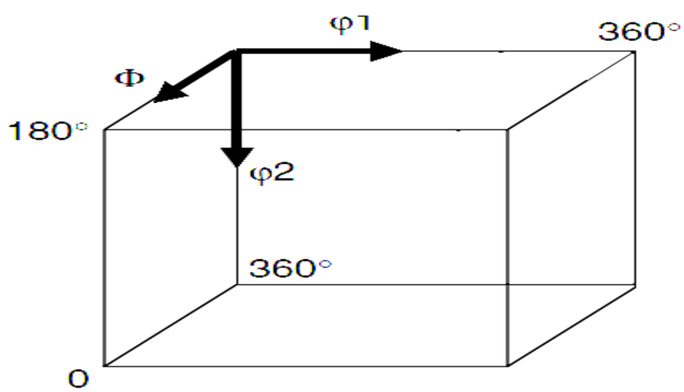


Fig2.7 Graphical representation of crystallographic orientations with Euler angles [19].

2.4.6. TEXTURE DEVELOPMENTS IN CRNO SILICON STEELS

The magnetic properties of silicon steels such as magnetization curves, permeability and core losses are correlated with metallographic properties like microstructure and crystallographic texture [20], [21], [22]. The resulting properties of materials are controlled by thermo-mechanical processing [20],[21],[22],[23],[24],[25],[26] which involves hot rolling, cold rolling and final recrystallization annealing. The rolling temperature and the coiling condition showed dependence on microstructure and texture evolutions during hot rolling [23],[24],[25]. This resulting texture is affected by the final properties of the cold rolled and recrystallized sheets [27]. Hot rolling in the austenitic region results in development of a final microstructure with a low magnetic induction quite contrary to hot rolling in the two phase region which ensures good magnetic properties [28][29]. The amount of deformation reduced and decrease in the hot rolling temperature typically induces improved magnetic induction in non-oriented electrical steels [28]. In addition hot band annealing results in enhanced permeability in silicon steels [30][31].

The various texture components that are observed in a non-oriented electrical steels can be generally classified into 7 categories namely Goss {110} <100>, cube {100} <001>, rotated cube {110} <110>, theta {100} <uvw>, eta {hkl} <100>, gamma {111} <uvw> and alpha {hkl} <110> [30]. Among these 7, cube texture is most desirable because {100} planes have greatest numbers of <100> axes. Texture with {110} planes have relatively larger number of <100> and <110> axes which are also desirable. On the other hand, the texture with {111} planes containing no <100> axes and the texture with {112} planes including <111> axes are undesirable and should be avoided for non-oriented steels. As a consequence, the ideal textures for non-oriented electrical steels are in the sequence of: cube {100}<001>, Goss {110} <100>, theta {100} <uvw>, eta {hkl}<100>.[32]. The final texture developed in any non-oriented steels is influenced by all the textures developed during every processing step i.e. hot rolling texture, hot band annealing texture, recrystallization texture and texture during grain growth which are described as follows:

In hot rolling the texture with low intensity of {110} <001> and {112} <111> are found [33]. Hot rolling also gives rotated cube {110}<110> orientation which is interesting for magnetic applications [34]. Hot-band annealing at a higher temperature is very effective to obtain both high magnetic induction and low core loss which are very essential, while it enhances the anisotropy of magnetic properties which is detrimental for a motor or generator manufacture [35]. These effects of hot-band annealing can be explained principally by the texture effect. The increase in planar anisotropy by hot-band annealing may be closely related to an increase in the {110} component and decreases in the {211} and {222} components. Recrystallization texture is one of the most important textures because the maximum texture property variation occurs between cold rolling and annealing when new strain free grains are induced from the strained lattice. The various texture components which are observed during recrystallization are namely Goss {110}<100>, cube {100}<001> and gamma fiber {111} <uvw> components [36]. The intensity of Goss component is strongest. The general rule which governs texture development during grain growth in electrical steels can be proposed as follows: for a texture component to be strengthened during grain growth, the grains of specific orientations should have not only a size advantage over other orientations but also a higher frequency of high angle, high energy grain boundaries [37]. The texture of the final products is also greatly affected by the microstructure prior to cold rolling, the quantity of inclusions and the reduction of cold rolling. When a hot-rolled sheet is annealed to increase its grain size, the development of recrystallized grains with {111} planes, from the original grain boundary, is suppressed, whereas the development of recrystallized grains with {100} planes is enhanced in cold-rolled and final-annealed products. Though, it requires more production cost the two-stage cold rolling method also being practiced to get better texture. In Figure 2.8 represents some of the important texture components at a constant φ2.

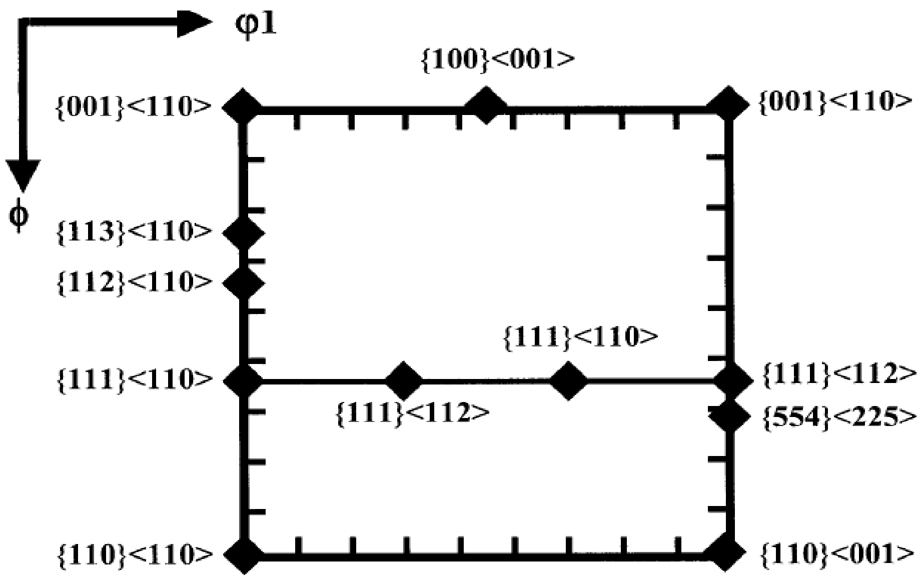


Fig 2.8 Schematic representation of the most important texture components in the ϕ2=45° section of ODF [38].

2.5. X-RAY DIFFRACTION

Texture is measured by X-ray diffraction. The XRD process is basically used to observe the macro or bulk structure of a sample

2.5.1 FEATURES OF X-RAY DIFFRACTION METHOD

XRD method is featured by large penetration depth (5 μm) and a spatial resolution ranging from 25 μm (with X-ray capillary optics) to 1 mm. Figure 2.9 shows the basic method of X ray diffraction.

Advantages of using XRD

- It provides well established technique.
- Relatively a large area is scanned in one scan.

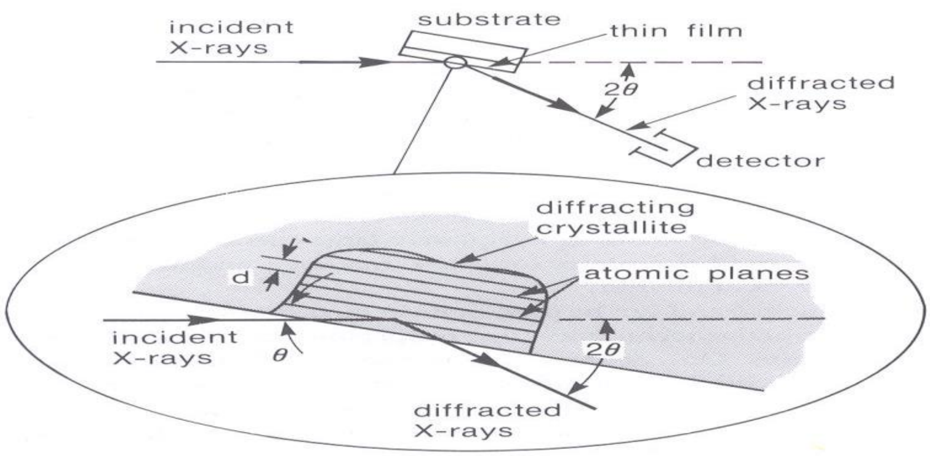
- Quite a large number of grains (tens of thousands) can be studied in one experiment.
- Macroscopic samples is usually examined by XRD.

Limitations of using XRD

- Calculations of orientation distribution function from pole figures is complex and and may give wrong informations.
- Poor spatial resolution – it is not suitable for microscopic samples which makes it difficult to relate texture to microstructure.

X-Rays and Texture Analysis

- Grains are visible under a microscope, but the orientation of the unit cells within those grains cannot be observed.
- X-Rays and electrons are basically diffracted from atomic planes.
- Varied arrangement of planes (texture) shows differences in the various diffraction patterns.



2.9 Basic method of X Ray Diffraction

CHAPTER 3:

MATERIALS AND EXPERIMENTAL PROCEDURE

3.1 MATERIALS

Hot rolled silicon steels of 2.3 mm thickness are subjected to cross-rolling at 10% true strain of 0.5 mm thickness reduction in a laboratory rolling mill. The cross-rolled samples are then subjected to annealing at 850°C for 1hr. the chemical composition of the silicon steel is shown in table 3.1.

Table 3.1 The Chemical composition(in wt. %)of Silicon steel sample.

C	Si	P	S	Mn	Al	Fe
0.039	1.52	0.0216	0.02	0.35	0.0525	Balance

From cross-rolled and annealed silicon steel sheets, samples are prepared and observed (1) in the rolling direction (2) 45˚ to the rolling direction (3) 90˚ to the rolling direction for different characterization.

3.2. TEXTURE CHARACTERIZATION

The bulk texture characterization was performed by a Panalytical MRD X-ray diffraction system at IIT Bombay and is used for the present study. Four different pole figures, (100), (110), (111) and (112) were measured. Subsequently the ODF was estimated using an academic software Labotex.

3.3. MAGNETIC PROPERTIES

The magnetic properties were measured by an equipment called PC based Pulse Field Hysteresis Loop Tester. A software is used to interface the system to the PC and the obtained datas are processed to calculate various hysteresis parameters like core loss and permeability of the sample.[39]

CHAPTER 4:

RESULTS AND DISCUSSION

Figures 4.1, 4.2, 4.3 provides the ODF plot of the samples at the three direction i.e. 1) the rolling direction, 2) 45° to the rolling direction, and 3) transverse direction respectively. Volume fraction of important texture components i.e. Goss and cube orientations is shown in figure 4.4. The figure clearly shows an insignificant variation of Goss and cube in the samples.

Inferring from the observation it can be concluded that the texture development in the three directions do not show any significant variation and thus, similar behavior is also shown by the magnetic properties of the sample. However, magnetic permeability at 45° to the rolling direction is less in comparison to other two directions as shown in the figure 4.6. The core loss though is similar in all the three directions as observed from the figure 4.5.

From the above observations it is concluded that the cross rolling of the silicon steel sample produced desired results with similar levels of core losses and insignificant variation in magnetic permeability.

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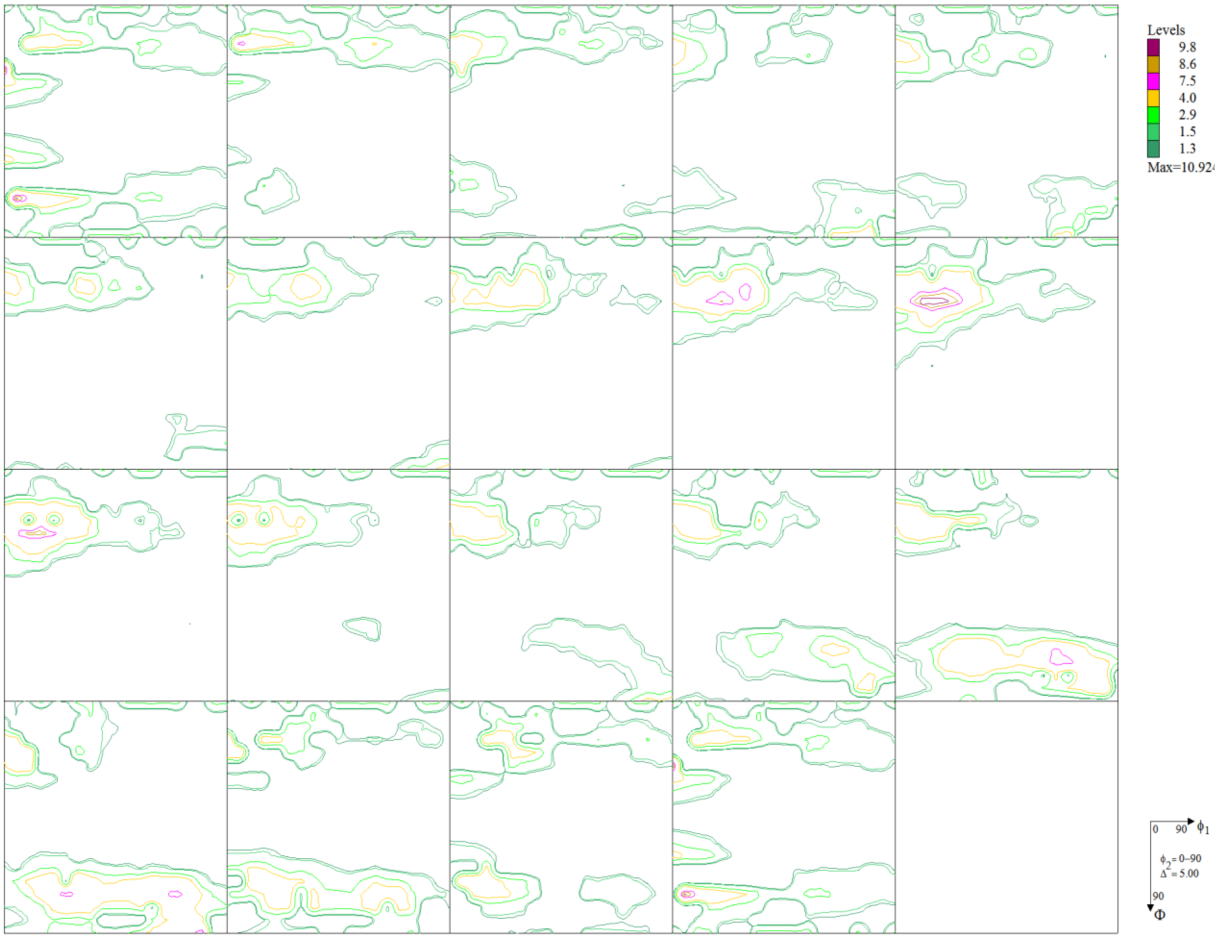

Figure 4.1 ODF plot, at constant ϕ_2, of silicon steel sample in the rolling direction.

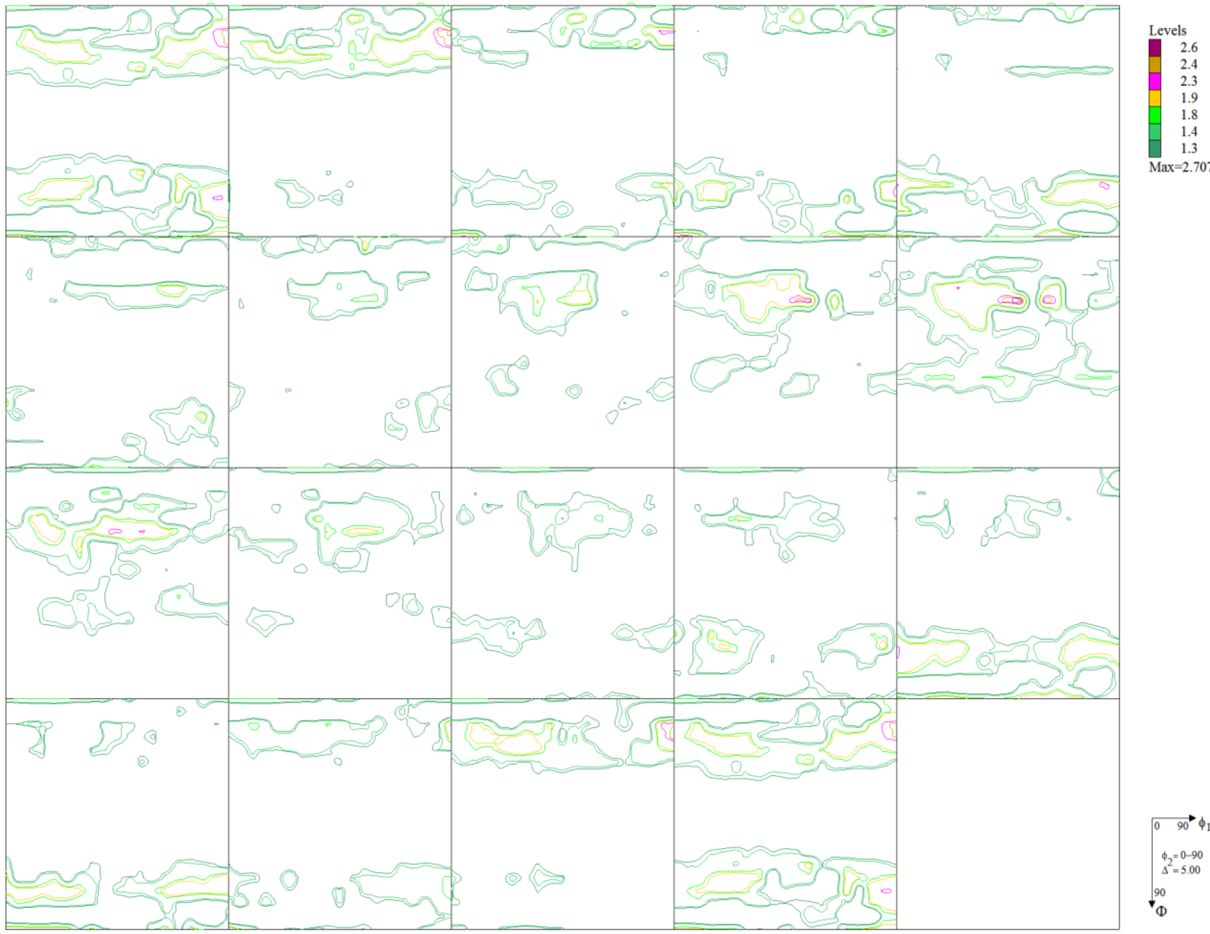

Figure 4.2 ODF plot, at constant ϕ_2, of silicon steel sample in the direction 45^o to the rolling direction.

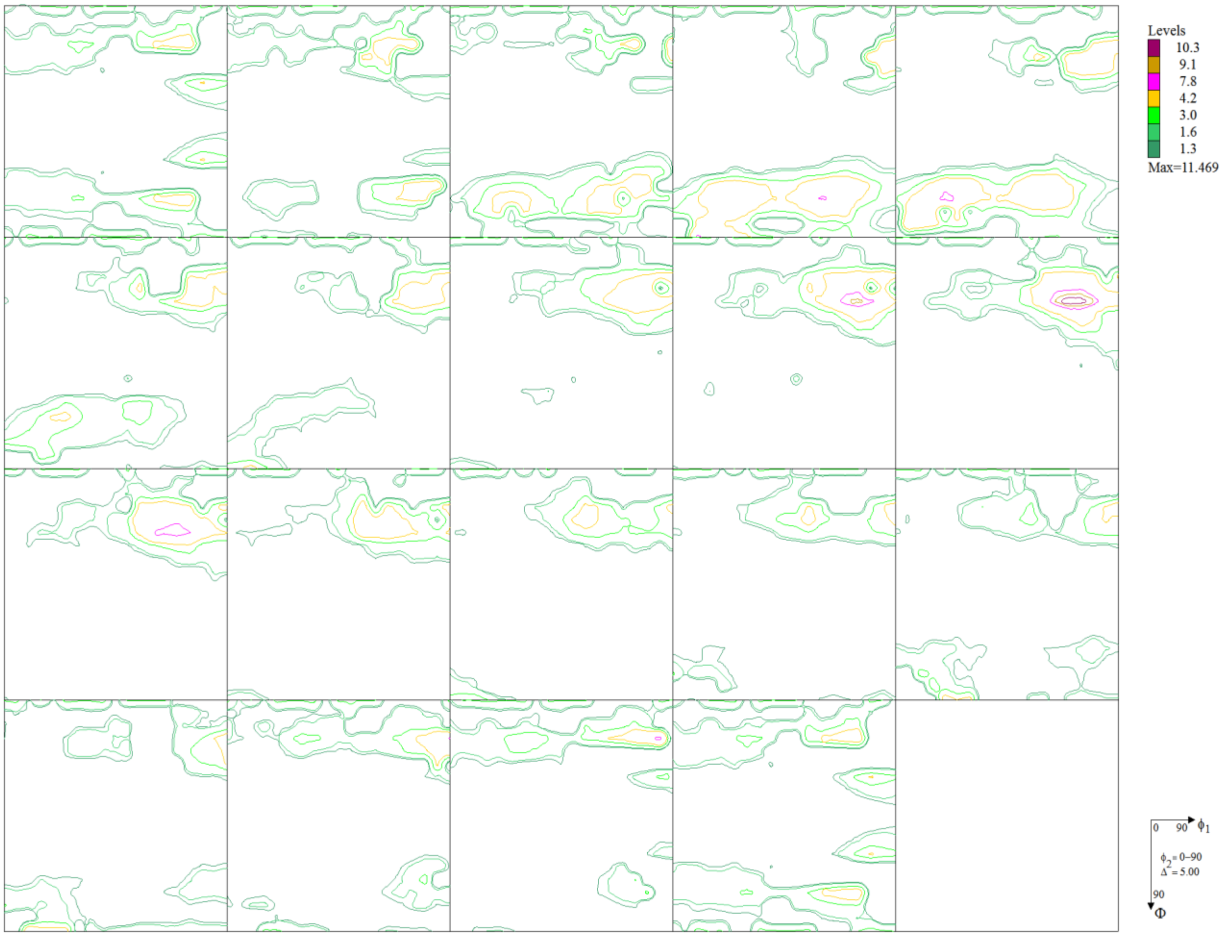

Figure 4.3 ODF plot, at constant ϕ_2, of silicon steel sample in the transverse direction.

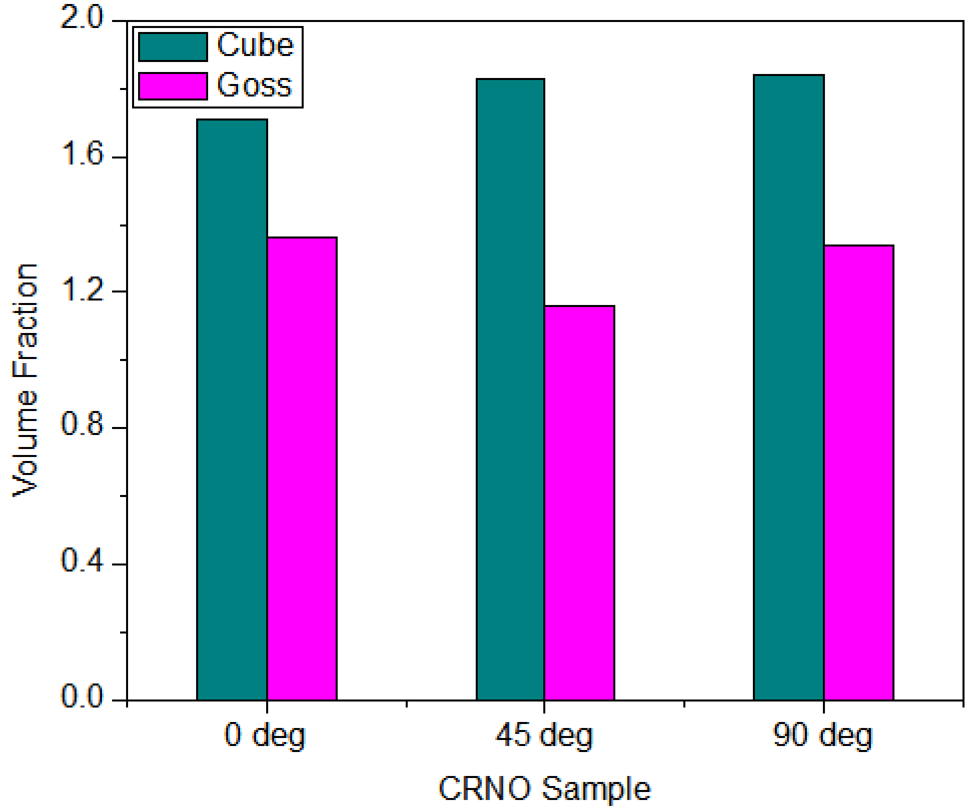

Figure 4.4 Volume fraction of cube, (001)<100> and goss, (110)<001> orientations at different directions of silicon steel sample.

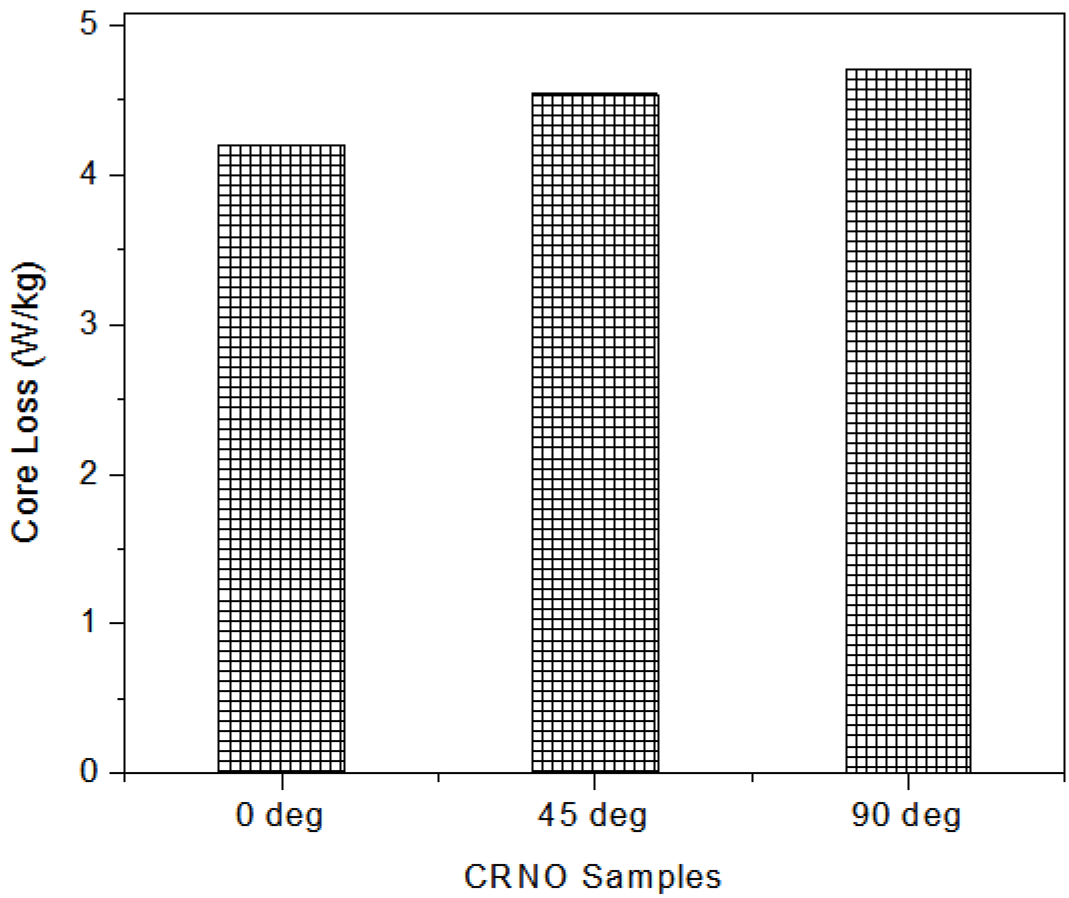

Figure 4.5 Estimated core losses of silicon steel sample at different directions.

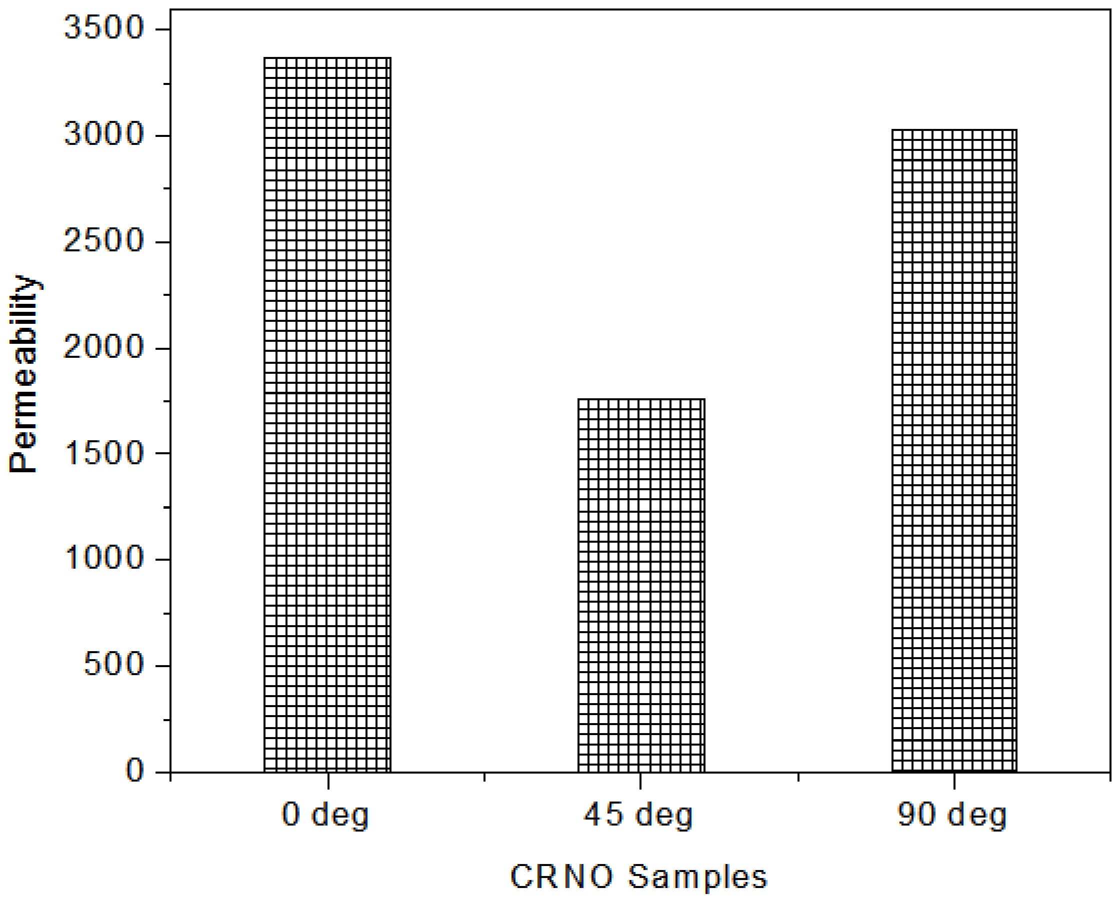

Figure4.6. Estimated permeabilities of silicon sample at different directions.

CHAPTER 5

SUMMARY

Texture and magnetic properties of the Silicon steel of 1.52% Si content was analyzed and investigated at different directions, i.e., in the rolling direction, at 45° to the rolling direction, in the transverse direction. From the results, the following conclusions are made:

- The volume fraction of the cube and Goss texture components are similar in all the directions.
- Magnetic permeability in the 45° direction is a little small in comparison to the other two directions.
- Core-loss observed in all the three directions are similar which show the ability of silicon steels to be used in the electrical devices.

RECOMMENDATION

The present study is a preliminary study of texture and magnetic properties of silicon steel which is done at basic laboratory scale .This is done by hot rolling the sample followed by cross rolling. The permeability observed is similar in all the directions except in 45° to the rolling directions. To achieve uniform properties in all the directions proper annealing steps may be carried out (as performed industrially). Future studies can be done by varying temperature of annealing for optimum properties of silicon steels.

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