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Thermo-mechanical Processing Evolution in Electrical Steel

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Abstract - Electric steel is a special type of steel used in different applications such as manufacturing the core of electric transformers, this type of material has customized magnetic properties, where its crystal structure contains iron with small additives like silica. In this project the electric steel will be investigated in order to improve its physical and magnetic properties. The main factors will be considered in this improvement are the composition, microstructure and crystallographic orientation of electric steel during the manufacturing process. In this paper, an improvement for the physical and magnetic properties of the electric steel was provided by studying the effect of annealing parameters and thermo-mechanical processing on the properties of electric steel and then finding a relation between the magnetic properties and crystal structure materials. The results of experimental investigation shows the average orientation angle for the microstructure about 15 °.

Keywords- electrical steel, GOSS orientation , annealing.

I. INTRODUCTION

In recent times, stringent government regulations have been passed internationally in controlling the global warming to an acceptable level. This has increased interest in using energy-efficient transformers on a national level which makes use of grain oriented electrical steel in core material and are comparatively costlier than conventional transformers [1]. Since the fact of improved magnetic properties by addition of silicon (Si) content was discovered by Hadfield et al. in 1900 followed by the discovery of magnetic isotropic properties of iron crystal in 1926 by Honda and Kaya, electrical steel has been increasingly produced and used in developing electrical equipments. Later, Goss discovered, in 1934, electrical steel sheets with grain oriented crystalline texture which showed remarkable improvements in magnetic characteristics due to the reason that the orientation of silicon particles was controlled in specific direction [2].

Grain Oriented Electrical Steel (GOES) is a soft ferromagnetic material with a crystal structure that contains primarily iron with addition of silicon content that helps reduce eddy current losses / power losses and highly permeable in nature. These modified magnetic properties of grain oriented electrical steel by addition of Si are of paramount importance in applications such as core material in electrical equipments i.e. generators for power generation, transformers for distribution and transmission and motors for final consumption to deliver required output. Another application of grain oriented electrical steel gaining attention is in magnetic shielding [2].

This study primarily highlights the identification of major factors during manufacturing and their impact in improving physical or magnetic properties of grain oriented electrical steel. In addition, this study also includes the effect of annealing parameters as well as thermo – mechanical process parameters on magnetic properties of grain oriented electrical steel.

II. LITERATURE REVIEW

a) Role of process control parameters

Various engineering applications necessitate thorough understanding and optimization of different process control parameters in improving physical or magnetic properties of grain oriented electrical steel. If controlled in a systematic way; process parameters such as composition of steel, microstructure as well as crystallographic orientation of electrical steel plays an important role in improving magnetic properties. Electrical steel needs to be deformed and annealed in

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controlled manner in order to produce acceptable texture form necessary for improvement in magnetic characteristics. A typical Goss texture {100} <001> in grain oriented electrical steel favours low eddy current (power) losses and highly permeable nature. This example highlights in details the effect of annealing in progression of different textures of hot rolled grain oriented electrical steel in annealed, cold rolled and re-crystallizing process conditions [3, 4].

b) *Multi-stage production procedure of grain oriented electrical steel*

The production of grain oriented electrical steel having sharp Goss texture with improvised magnetic characteristics involves operations with complex multi-stage processes under careful supervision [3, 4]. The multi-stage process (**Figure - 1**) for production of grain oriented steel includes the following procedural steps [7]:

- Conventional steel producing process followed by continuous casting to form steel slabs.
- Reheating of casted slabs at 1400°C.
- Hot rolling of reheated slabs to 2-3 mm sheets.
- Annealing of hot rolled sheet at 1000°C for different time periods of 5 and 100 minute at cooling / heating rates of 5 °C/min to evaluate texture evolution.
- Two-stage cold rolling process including an intermediate annealing or single-stage cold rolling process involving sheet thickness reduction to large extent.
- Final stage involves re-crystallization annealing, firstly for de-carburizing sheets in a wet hydrogen environment and secondly in a dry hydrogen environment.

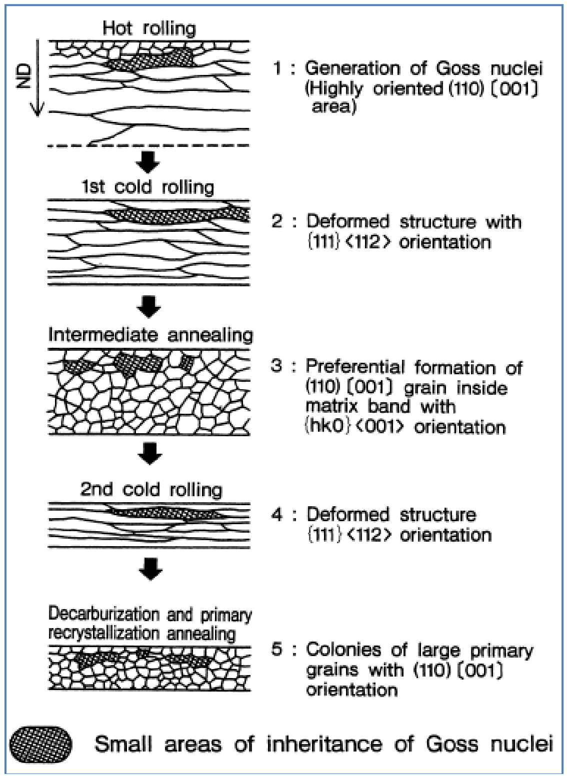

Figure 1: Schematic Multi-stage Process Diagram – Hot – Rolled Silicon Steel Sheet [5]

The specimens were etched with 4% Nital solution before the microstructure and micro-texture examinations of sections RD - TD and RD - ND (rolling R, transverse T and normal N directions respectively) were performed using optical microscopy. For examining microstructure and micro – texture of RD – ND section, electron backscatter diffraction (EBSD) method was used. Due to the possibility of using Electron backscatter diffraction in combination with Scanning Electron Microscope (SEM), it is now easier to evaluate grain orientation along with grain energy storing capabilities Estimation of stored energy of grain oriented cold – rolled materials is a better resource to understand mechanisms of re-crystallization and recovery. The test specimens used for examination in scanning electron microscope must be polished with colloidal silica for at-least 20 minutes before placing in the microscope [3].

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c) *Evolution of microstructure and micro-texture during hot-rolling*

The microstructure and micro-texture of RD – ND cross-section of the specimen taken from hot-rolled grain oriented electrical steel is shown in **Figure - 2**. The figure demonstrates the inverse pole figure – normal direction EBSD based map overlapped with grain boundary having angle more than 15°.

As is clear from the inverse pole figure, the microstructure of the test specimen across its thickness represents heterogeneity in grain size, shape and aspect ratio. The grain shape closer to the surface of grain oriented steel specimen is equi-axial whereas the middle region of the specimen across its thickness is occupied with elongated grains of pancake – like geometry. The cause behind equi-axial grains on the surface is the reduction in surface temperature due to water sprays during the process.

Due to this reduced temperature on the surface of steel sheet while rolling, the contact between defects reduces which lead to high energy build up in grains close to steel sheet surface [3].

In hot – rolling process of steel, the high shear stresses are experienced on the steel sheet surface while the middle region across the thickness experience plain strain conditions leading to deformation of grain under varying stress scenarios throughout the cross-section of specimen [10].

The combined effect of high shear stresses and high energy build up in grains reduces dynamic recovery and gives rise to re-crystallisation of grains near the surface. This re-crystallisation leads to equi-axial geometry of grains close to the surface of hot-rolled grain oriented electrical steel sheet. The temperature in the middle region of steel sheet specimen remains unaffected and sufficiently high enough to initiate dynamic recovery of grains resulting in pancake – like geometry of elongated grains [3].

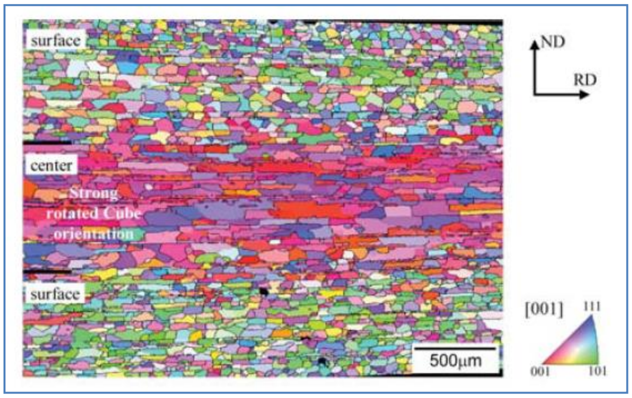

Figure 2: Inverse Pole Figure - Normal Direction EBSD Based Map [3]

As clearly visible for **Figure – 3**, the grains texture close to the surface contains strong {112} <111> and {110} <112> components as well as weak Goss components. Development of these strong texture components is the outcome of shear deformation on the surface and gradually becoming weaker in the mid-surface region of hot – rolled grain oriented steel sheet. It is because of the variations in temperature, shear stresses and strain rate across the thickness of steel sheet. The grains in the mid-surface region experience plain strain deformation as shown in Figure - 3. The strong texture components {001} <110> in the middle region are represented by α-fibre and the weaker ones are termed as γ-fibre. The variations in deformation from shear strain near the surface to the plain strain in the mid-surface region leading to heterogeneity of the microstructure as well as texture gradient all over the thickness are the observations of the experiment performed [3].

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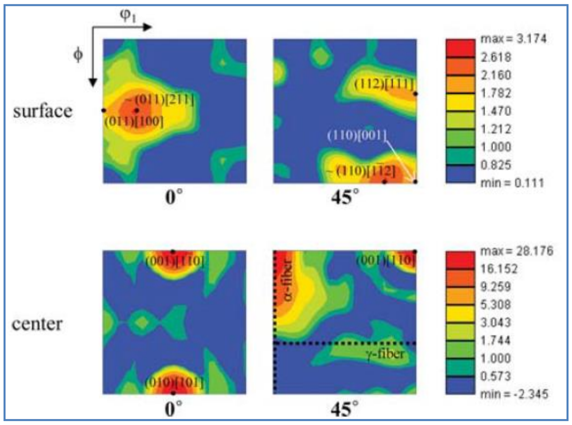

Figure 3: Orientation Distribution Function at φ2 = 0° and 45° for surface and mid-surface (center) regions [3]

d) *Effect of annealing on crystallographic grain orientation*

To understand the effect of annealing, the hot – rolled specimens were allowed to anneal for two different time- periods 5 min and 100 min respectively. Referring to **Figure – 4 and 5**, it is clear that grains all over the thickness of steel sheet exhibited positive signs of growth and the grain size growth rate increased with longer annealing time. The grain size increment was recorded at approximately 8% in grains after 5 minutes annealing at 1000°C whereas a 10% increment in grain size was observed after annealing for 100 minutes. The hot – rolled specimen microstructure, however, did not show any signs of homogeneity after annealing and remained heterogeneous on the basis of grain size and geometry throughout specimen thickness [3]. The mid-surface region, after annealing for 5 and 100 minutes respectively, showed similar context in texture as was observed in hot – rolled grain oriented electrical steel with high intensity {001} <110> α-fibre. As per study performed by Tomida (1996) [11], a weak cube – like texture appeared in the specimen during annealing for 5 minutes which could be one of the leading causes in enhancing magnetic properties of the grain oriented electrical steel. Due to this reason, annealing for short period may be considered beneficial in generating favourable texture at relatively low production cost but needs further study to prove it.

Another observation from figures can be visualised that the grain texture on the specimen surface is much stronger when annealed for 100 mins than that of specimen annealed for 5 mins only [3].

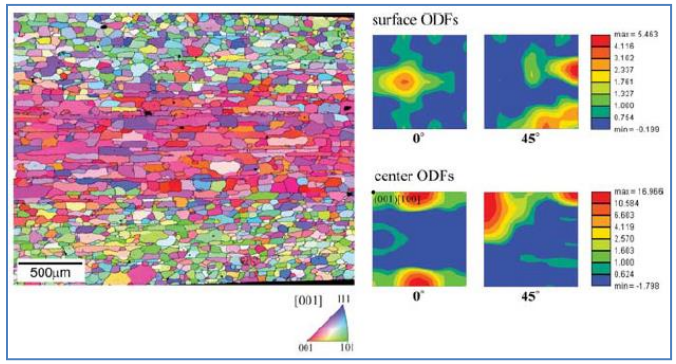

Figure 4: IPF-ND Map & ODF's at φ2 = 0° and 45° of hot – rolled electrical steel after 5 min annealing [3]

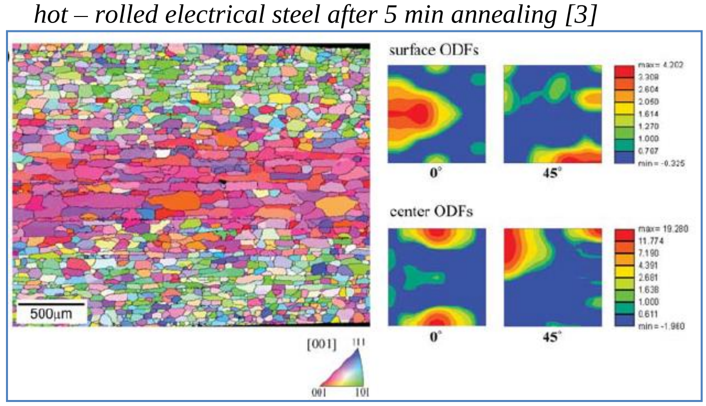

Figure 5: IPF-ND Map & ODF's at φ_2 = 0° and 45° of hot – rolled electrical steel after 100 min annealing [3]

Study performed by Dorner et al. (2007) [8] further revealed the existence of two different Goss oriented regions originated in cold – rolled material, one in shear bands and another in micro bands. However, during cold – rolling process, one of the Goss oriented region in the shear bands diminishes, leaving the other existed between the micro bands. The claims are made by the authors that remaining Goss oriented grains in micro bands may influence the development of Goss grains in grain oriented electrical steel while processing for primary re-crystallisation as well as for subsequent unusual Goss grain growth in secondary re-crystallisation. Thus expecting more Goss – oriented grains in grain oriented

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electrical steel specimen annealed for 100 minutes compared to that for 5 minutes may be evident during secondary re-crystallisation. This study has highlighted the fact that annealing of hot – rolled grain oriented electrical steel is beneficial in grain growth to significant level but also exhibit its limitation in affecting the heterogeneity of the microstructure and micro texture of hot rolled steel specimen across its thickness [3, 4].

Major development in grain textures of steel sheet specimens after every stage of multi-stage production process were observed by incorporating EBSD method and reported. Superimposition of crystallographic grain orientation maps over image quality maps is shown in **Figure – 6**. Goss oriented grain textures were identified in specimens produced after hot – rolling and annealing. The strong α-fibre components {001} <100> and {112} <110> were identified throughout every stage starting from hot – rolling to cold - rolling process. Their presence can be observed in mid-surface region of specimens after hot – rolling and annealing. Six major crystallographic grain orientations, as mentioned in **Figure – 7**, were observed during the experiment are as follows:

- Goss Orientation - {110} <001>
- Cube Orientation - {100} <001>
- α – fibre components (rotated cube orientation) - {001} <110>
- γ – fibre components - {111} <112>
- γ – fibre components - {111} <110>
- α – fibre components - {112} <110>

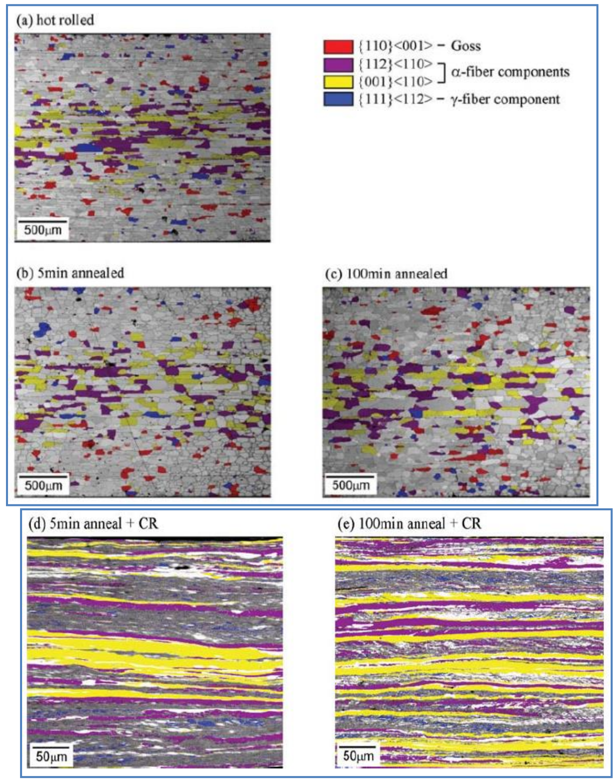

Figure 6: *Superimposed crystallographic orientation maps and image quality maps of steel sheet specimen [3] at different stages [hot – rolling (a) to cold – rolling (e)] of production process*

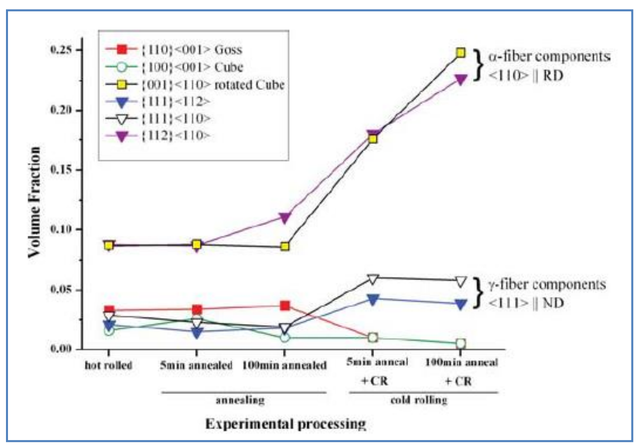

Figure 7: Six major crystallographic orientation volume fractions of grain oriented steel sheet specimen [3]

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at different stages [hot – rolling (a) to cold – rolling (e)] of production process

As visible from figure – 7, the volume fraction of Goss oriented grain texture components remained almost constant during hot – rolling and annealing but started reducing during cold – rolling process whereas the volume fraction of weak γ-fibre {111} <110> and {111} <112> texture components showed increment during cold – rolling stage due to rotation of Goss components in mid-surface region. The cold – rolled steel sheet specimen also contains strong {112} <110> texture components across its cross section. The sudden rise in volume fraction of strong {112} <110> texture components is mainly because of the fact that the specimen was annealed for 100 minutes before cold - rolling whereas the volume fraction of cube orientation grains in steel sheet specimen remained low and almost constant throughout all stages of production process. The volume fraction of all six major crystallographic grain orientations of grain oriented steel showed small changes during annealing for 100 minutes whereas Goss oriented {110} <001> texture components intensity decreased. For cube oriented texture {100} <001>, the volume fraction remained unchanged and remaining {001} <110>, {111} <112>, {111} <110> and {112} <110> components showed sudden rise in intensity during cold – rolling [3].

e) Influence of topology during secondary re-crystallisation

Like primary re-crystallisation process, secondary re-crystallisation is a process of evolution of texture components through grain growth. Decrease in Grain boundary energy is the key that drives the secondary re-crystallisation texture formation process. Similar to primary re-crystallisation, either *grain oriented growth* or *texture crystallisation* or the combined effect of the two can be considered in explaining the texture formation during secondary re-crystallisation. Decrease in grain – boundary energy is caused not only by unusual grain growth but also by normal grain growth during secondary re-crystallisation in comparison with primary re-crystallisation process. Beginning of abnormal grain growth is only possible once normal grain growth slows down. To slow down normal grain growth, uniformly dispersed fine precipitates / solute atoms of inhibitors are used to hold grain boundaries. Another way of slowing down normal grain growth is by the presence of strong and sharp primary re-crystallisation texture. The existence of low angle grain boundaries between major proportions of the grains reduces normal grain growth leading to abnormal growth of remaining strongly deviated grain orientations [6, 9].

The inhibition of normal grain growth is possible by fine dispersed particles of aluminium nitride or manganese sulphide in primary re-crystallised electrical steel during formation of Goss oriented texture. However, the primary re-crystallised texture does not inhibit normal grain growth due to its weak nature. Experiments performed by May and Turnbull (1958) [12] has previously revealed the absence of abnormal grain growth in highly pure silicon steel due to the non-existence of secondary phase particles [9].

Grain oriented growth has been considered the most favourable approach in past researches to understand texture formation mechanisms. For this purpose two different models have been studied. The first model considers the abnormal grain growth of Goss oriented grains is due to coincidence site lattice (CSL) grain boundaries. This is due to the fact that compared to other grain orientations during primary re-crystallisation, Goss oriented grains have higher tendency to take participation in the formation of low – Σ coincidence site lattice grain boundaries. CSL boundaries are the boundaries consisting of large number of lattice coincidence locations.

This model is a concept based on geometrical interpretations which is used in deriving physical mechanisms like solubility of foreign atoms or dislocation mechanism related to grain boundaries and its existence has no physical meaning. Another model considers high angle boundaries involving mis- orientation angle within a range of 20° to 45° for their highly mobile behaviour. Large diffusions along these boundaries during annealing tend to coarsen the precipitates much faster turning them into large size particles.

These particles exert lesser restraining force on moving grain boundaries compared to smaller particles. This tendency makes the Goss oriented grains to be bounded by large number of highly mobile grain boundaries leading to abnormal growth of Goss oriented grains [9].

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The observations made from the experiment performed in this study was to understand the topological benefits like size or number of subsequent nearby primary re-crystallised Goss oriented grains in development of sharp Goss texture in grain oriented silicon steel during secondary re-crystallisation. The examination leads to two different kinds of measurements using automatic crystallographic orientation measurements (ACOM) involving field emission gun scanning electron microscope (FEGSEM) on a layer of specimens' subsurface that have been primary re-crystallised [9]. Primary measurements were determined for the size and number of subsequent nearby grains including orientation distribution of a major proportion of grains. Tendency of large sized grains or grains with subsequent nearby grains to be next to Goss oriented grains was not experienced. The secondary measurements involved the examination of orientation distribution of large sized grains.

Weak presence of Goss oriented grains on η-fibre in the Euler orientation space region were observed whereas the large sized grains occupied most of the η-fibre orientation components. The grains observed close to Goss oriented grains were particularly smaller in size rather than being large size. Also, the large sized grains were examined to be more than 20° away from Goss oriented grains [9].

During investigation, a mid size grain next to Goss oriented grains exhibited high quantity of subsequent nearby grains which could possibly be the sign of the presence of Goss nucleus as can be seen in **Figure - 8**. However, some highly deviated grains with respect to Goss orientation exhibited similar nature involving high quantity of subsequent nearby grains raising concerns in exactly identifying Goss nucleation characteristics during secondary re-crystallisation. Thereby, it is difficult to explain the effect of topological benefit alone on the development g Goss oriented grain texture during secondary re-crystallisation [9].

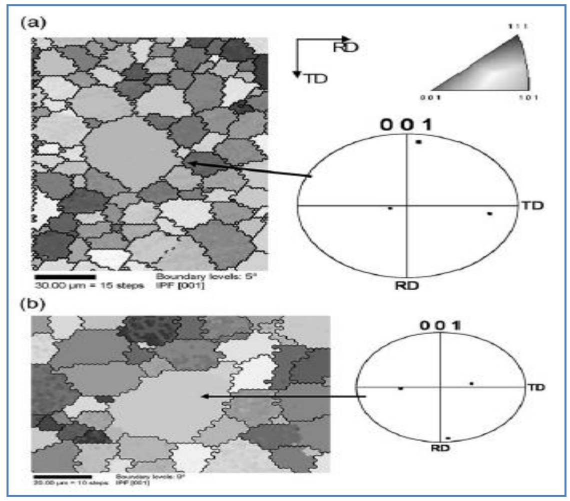

Figure 8: Crystallographic orientation maps of large size primary re-crystallised steel sheet specimen [3] Large size grain orientation is shown as 001. (a) Large size grain on η-fibre (b) Goss grain with subsequent nearby grains

III. EXPERIMENTAL PROCEDURE

A) introduction

The changing of composition for the electric steel effect on the electrical properties such as the electric resistivity as example when the silica content increases , the electrical resistivity will increase which reduce the losses if the material is used in core of electric transformers. Crystallographic orientation depends on the recrystallization of the steel, where the recrystallization can be achieved by heating the material over crystallization temperature. However the first recrystallization electric steel produces GO electric steel and the second recrystallization produces Goss electric steel. In this work, the effects annealing parameters and thermo-mechanical processing on the properties of electric steel were investigated to find a relation between the magnetic properties and crystal structure materials, so different tools were used to understand crystal orientation, domain structure, microstructure, mesotexture and microtexture.

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b) Experimental steps

the first step of experimental procedure is grinding , figure bellow shows the device are used for grinding and polishing which is called BUEHLER AUTOMET’ 250 machine .

Figure 9: BUEHLER AUTOMET’ 250 machine

auto grinding is applied for 2 minutes grinding using different grinding wheels 600/800, then 1200 and 2500 grinding wheel were used respectively with water agent , however the based and head speed were calibrated as 150 , and 50 rpm respectively . After completing the grinding stage the polishing was used for 2 min with calibrating the based and head speed as 250, and 50 rpm respectively. The diamond suspension was added with sizes 3,6 and 9 μm Small amount was added per minute figure below shows an example for the diamond suspension. The final polishing was applied to get very fine surface where the based and head speed were calibrated as 80 , and 50 rpm respectively.

Figure 10: diamond suspension with size 3 μm

The microstructure was investigated using a digital microscope (Keyence), where this device is connected to display screen can be used to change the zooming and its location. The following Figure shows this device

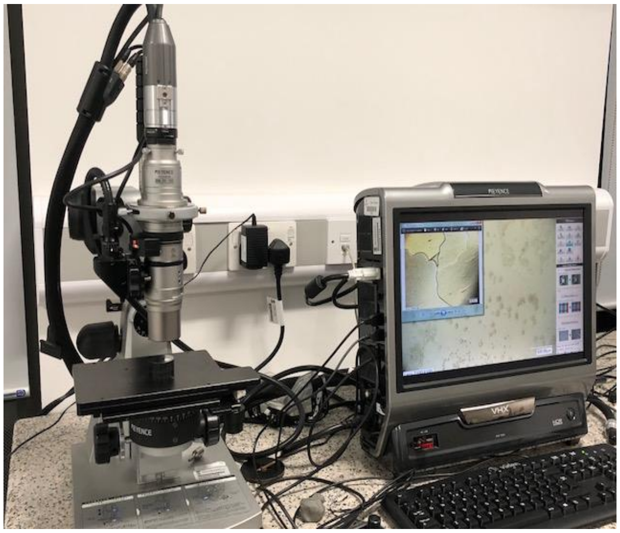

Figure 11: Keyence digital microscope

IV. RESULTS AND DISCUSION

The microstructure of Grain oriented silicon steel 3.2% Fe-Si was analysed using different zooming scales as shown in the following figures , where the grain boundaries angle was measured for the different grains as shown below .the angle for the different measurements on the first image of microstructure, where the average value for the angle approximately is 11° .

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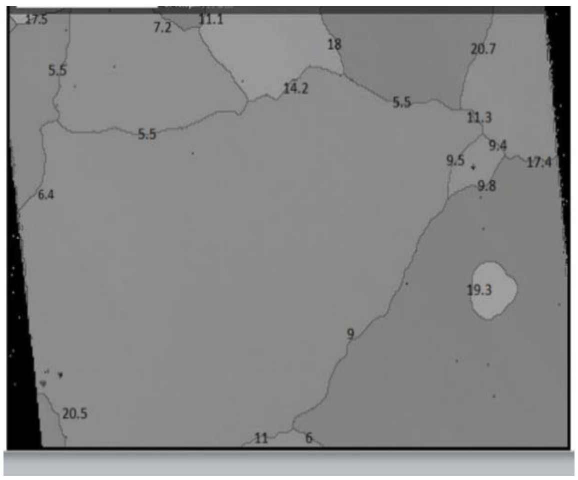


Figure 12: microstructure for the first capturing of microstructure

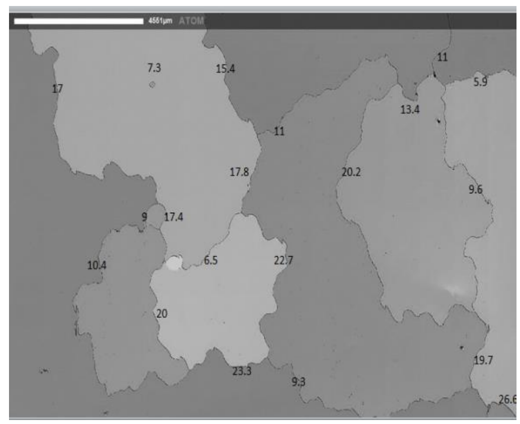
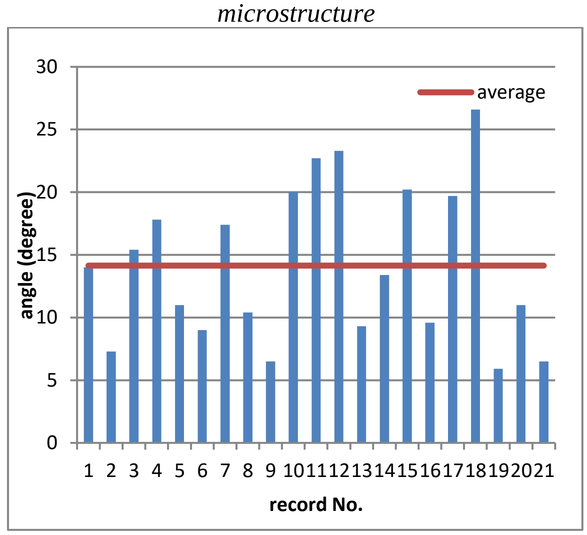


Figure 14: microstructure for the second capturing of microstructure



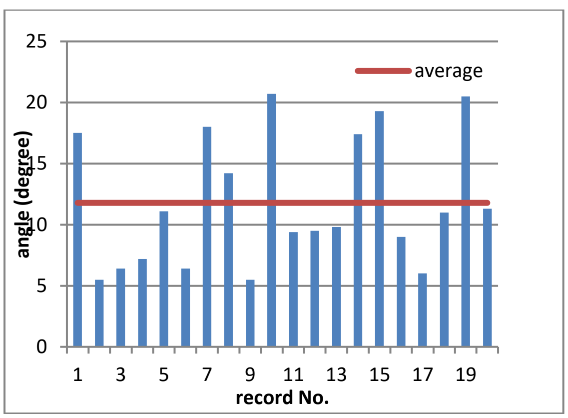


Figure 13: the measured orientation angles for the first capturing of microstructure

To validate the results of other microstructure image was obtained as shown in the following figure , where the angles for the different records shows the average value is value is 14.14 °.

Figure 15:the measured orientation angles for the second capturing of microstructure

Figure 16 shows the third results where figure 17 shows the average angle 15.7 °. The last analysis was obtained in figures 18 and 19 where the average angle also about 15.7 °.

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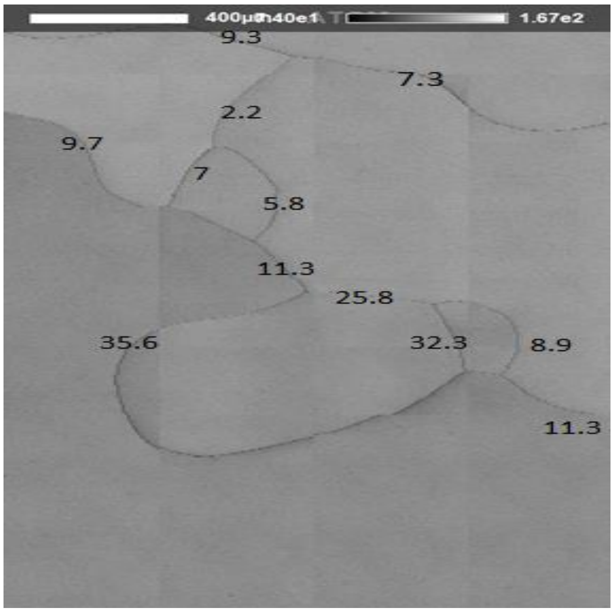

Figure 16: microstructure for the third capturing of microstructure

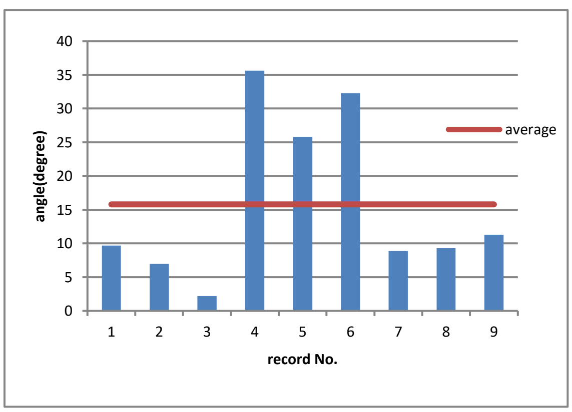

Figure 17:the measured orientation angles for the fourth capturing of microstructure

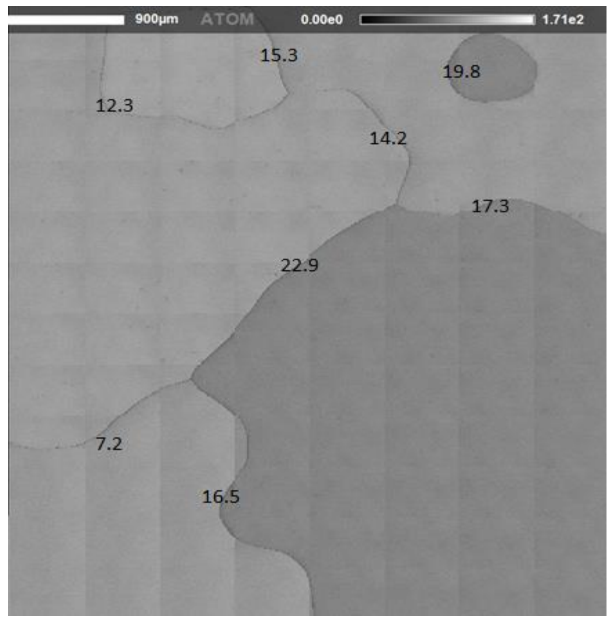

Figure 18: microstructure for the fourth capturing of microstructure

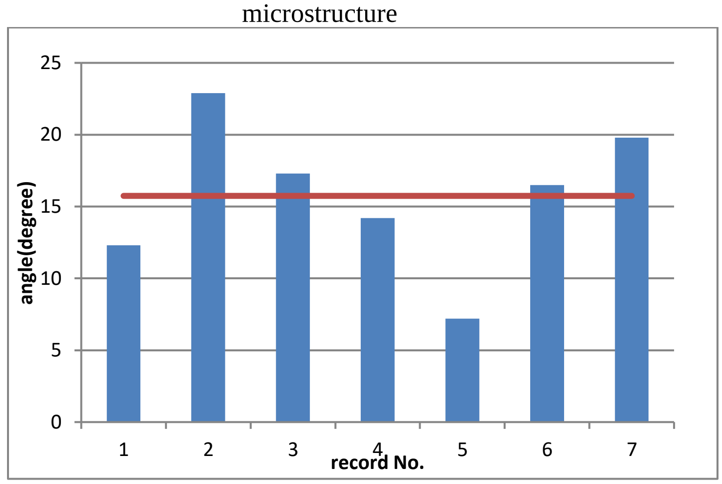

Figure 19:the measured orientation angles for the fourth capturing of microstructure

According to obtained results it can be noted clearly the orientation angle is closed or less than 15°, according to

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the GOSS orientation of the electrical steel which is in this range as mentioned by [13].

V. CONCLUSION

Grain Oriented Electrical Steel (GOES) is a soft ferromagnetic material with a crystal structure that contains primarily iron with addition of silicon content. The production of grain oriented electrical steel having sharp Goss texture with improvised magnetic characteristics. The changing of composition for the electric steel effect on the electrical properties such as the electric resistivity as example when the silica content increases , however the first recrystallization electric steel produces GO electric steel and the second recrystallization produces Goss electric steel. The microstructure was investigated using a digital microscope (Keyence). The electric steel was investigated in this project where the microstructure properties where considered by measuring the angles of orientation, the results were obtained for different capturing images, the results shows the angle of orientation is closet or less than 15°.

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