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Improvement in Magnetic Properties in Electrical Steel Grades

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ABSTRACT

The CRNO steels are used as core materials in electrical motors and transformers. Key properties governing the efficiency of the components are low core loss and high permeability. 50C600 grade with Si % between 1.3 to 1.4 is one of the most common grades in India. Variation in permeability (B50) was found in this grade, with variation from 1.65 Tesla to 1.70 Tesla. Detailed investigation was carried out to find the factors affecting the permeability. The most notifying source was found to be average inclusion size. Inclusions deteriorate the magnetic property by pinning the motion of domain walls. Presence of inclusion above 10 µm resulted in lower permeability. Subsequently use of diffuser in tundish was experimented for forced flotation of inclusions. Optimum gas flowrates were calculated mathematically and further adjusted with a series of experiments. Bubbling was kept normal and the back pressure was maintained constant during the sequence casting. Average inclusion size reduced from 12 µm to less than 8 µm in HR coils with the use of diffuser. In the coils having lower inclusions, average permeability improved from 1.68 Tesla to 1.7 Tesla in the coils produced with the use of diffusers.

Keywords: Tundish, Bottom bubbling, Inclusion flotation, clean steel, Magnetic properties.

1. INTRODUCTION

Cold rolled non oriented electrical steels, (CRNO) are produced from Fe-Si or Fe-Si-Al alloys and are tailored to produce specific properties like low core loss and high permeability. Non-oriented electrical steel sheets are incorporated into a wide range of equipment, from the simplest domestic appliances to hybrid and pure electric vehicles [1]. In these steels the magnetic properties like low core loss and high magnetic induction are required considering the energy conservation.

Many factors such as inclusions, texture and grain size can affect the magnetic properties, among which inclusions play significant role by affecting the other two factors. The inclusions can impede the motion of domain wall, thereby deteriorating the magnetic properties directly. The inclusions can also inhibit the movement of grain boundaries and promote the heterogeneous nucleation of grains with unfavourable orientations, thus, affecting the magnetic properties indirectly [2].

At JSW Steel, the CRNO grades being produced are found to have variations in permeability and in the lower side of acceptable limits. Especially in 50C600 grades of electrical steel, magnetic property, B50 value was found varying from 1.65T to 1.69T against the target of 1.69T consistently. Due to fluctuation in B50 value the downgradation of NOES coils was a major concern. Literature [3] shows that the grain size and Si content of NOES are the primary controlling factors to core loss, especially at higher frequencies. Crystallographic texture plays an important role at lower frequencies. At higher frequency, core loss increases with increasing grain size and decreasing Si content of the steels.

Pampa Ghosh [3] suggests that Permeability and core loss are structure sensitive properties and depend on several metallurgical factors like chemistry, grain size, crystallographic texture, cleanliness and stress states.

Permeability is affected by the processing parameters and steel quality. Especially the inclusions deteriorate the magnetic property by pinning the motion of the domain walls [2]. Hence it is important to classify and quantify the inclusion distribution and reduce the inclusion severity for improving the magnetic properties. Recent literature suggests that use of diffuser in tundish force the inclusion to float and results in cleaner steel. It is therefore, proposed to conduct trials with diffuser in Electrical steel grades and study its effect in the final electrical properties.

Sujata [5] investigated on inclusion removal by bubble flotation method in a two-strand tundish using computational fluid dynamics and through water model studies. Thus new technique of gas curtain made of small bubbles of argon called Tundish Argon Diffuser has been used to remove the finer inclusions from steel in order to produce clean steel.

Some literature [6-7] studied and analysed numerically the probabilities of inclusion removal from liquid steel by collision and attachment to rising gas bubbles. They concluded that inclusion removal rate in tundish is efficient by employing argon gas injection.

2. MATERIALS AND METHODS

The bottom gas bubbling is very widely used in ladle metallurgy for homogenization of composition and temperature and inclusion flotation in the later part of the secondary metallurgy treatment. The purpose of diffuser is the flotation of inclusion to the slag layer avoiding it to go to the steel melt and thus producing clean steel.

Diffuser is a refractory arrangement made of alumina. There are pores throughout the upper surface of diffuser; through these pores argon gas is passed which helps in flotation of inclusions. For taking trials of diffuser in electrical steel, tundish was prepared using diffuser. While preparing tundish, diffuser was placed at the bottom of slab tundish at some specific distance from SEN. At one end of the diffuser we have a small opening for fixing pipeline through which argon gas is passed as shown in Fig.1. This argon pipeline is connected with flow control valve to record argon gas flow rate and back pressure. The optimum gas flow rate was calculated theoretically. The calculated flow rate was used as the first approximation for the initial trials. After that argon flow rates were adjusted with a series of experiments seeing the disturbance of the slag layer.

While taking trials of diffuser in electrical steel, the casting parameters like casting speed superheat and mould flow conditions were kept constant to see the effect of diffuser on inclusion flotation. Plant trials with the use of diffuser was taken in electrical steel grade with Si (1.3- 1.4) % in the slab width of 1320 mm and thickness 220 mm. All trials were conducted with cold rolling grades. Optimized bubbling locations and calculated flow rates were used in the first set of experiments. With the use of bottom bubbling, it was ensured that the tundish level did not go down too low to create emulsification. Gas bubbling was stopped at the time of draining of tundish, in the last heat of the sequence. The casting speed was normal of 1 meter per minute.

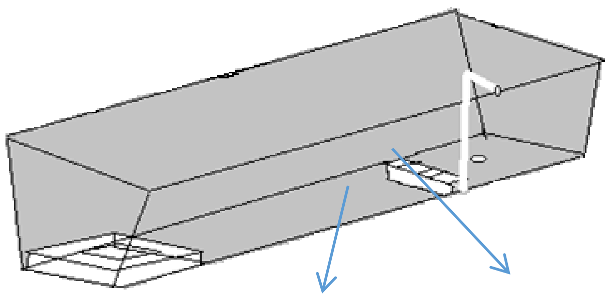


Fig.1

Schematic of diffuser arrangement in tundish

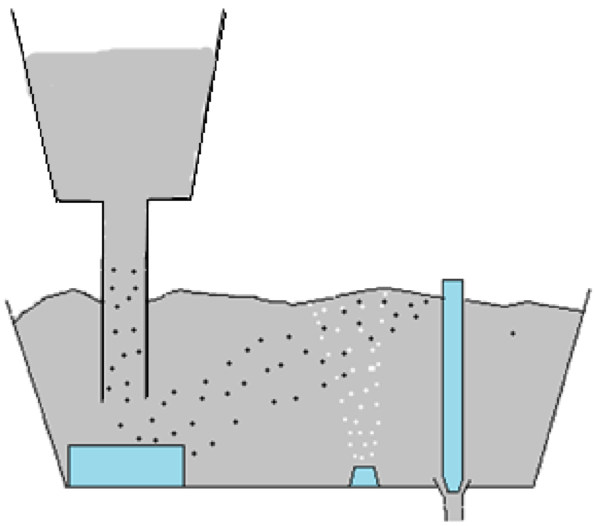


Fig.2 Application of diffuser showing flotation of inclusion

Application of diffuser showing flotation of inclusion while casting is shown in Fig. 2. After casting was over, the slab samples were collected at specific location for metallographic analysis of inclusion. The trials samples was collected at each stage as cast, hot rolled and cold rolled conditions for analysing the severity of inclusions.

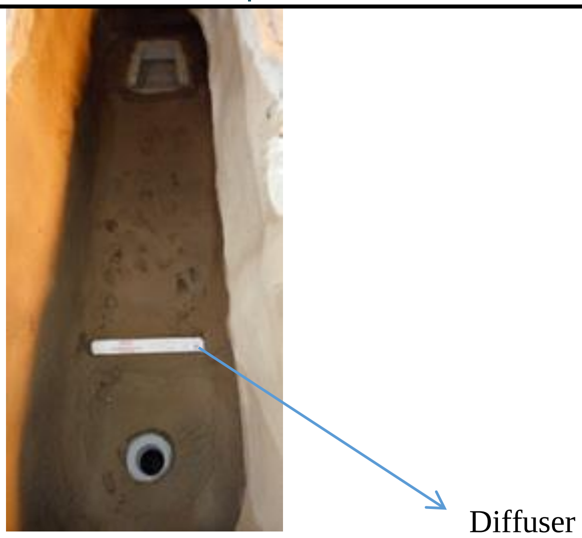


Fig. 3 Diffuser applied at the bottom of tundish

Electrical grades of steel are very critical grade and it requires special care in processing at each stages. Diffuser was fixed at the bottom of tundish at some specific distance from the SEN as shown in Fig. 3. Diffuser was used successfully in slab caster tundish. After casting was over, the condition of diffuser was seen after dumping. And it can be seen from Fig. 4 that there was no erosion found in diffuser while casting. Everything was found normal during the casting process. The rolling parameters at hot strip mill and cold strip mill were kept unchanged.

Fig.4 Diffuser at the end of casting

3 RESULTS AND DISCUSSION

3.1 Influence of De-oxidation practice and Mould Level fluctuations:

Detailed investigation was carried out to find out the factors affecting the permeability in electrical grade steel. The process parameters were checked starting from casting to hot rolling and cold rolling. Data analysis was done and the scope of improvement was seen in cleanliness of the steel. Various steel cleanliness parameters in steelmaking and casting was checked like de-oxidation time, superheat, casting speed, mould level fluctuation and usage of tundish covering compound. A strong correlation was found with de-oxidation time and mould level fluctuation affecting magnetic property, B50. It can be seen from Fig. 5 that as the de-oxidation time increases permeability is increasing. More de-oxidation time means more time for inclusions to float to the slag layer and thus more clean steel. And Fig. 6 infers that higher mould level fluctuation results in lower permeability.

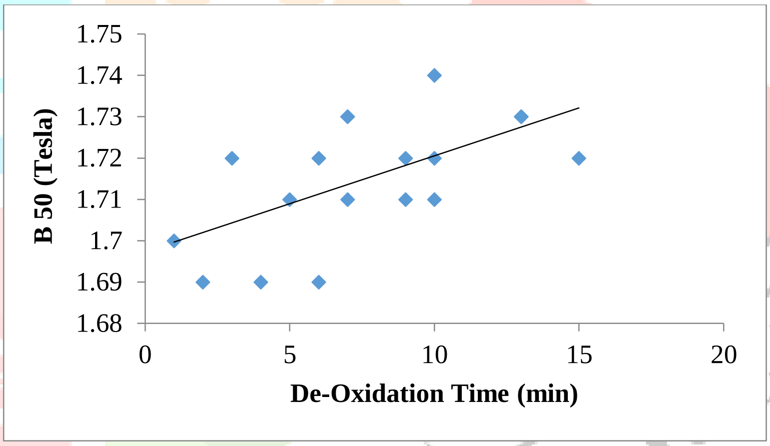


Fig. 5 Effect of De-oxidation time on Permeability

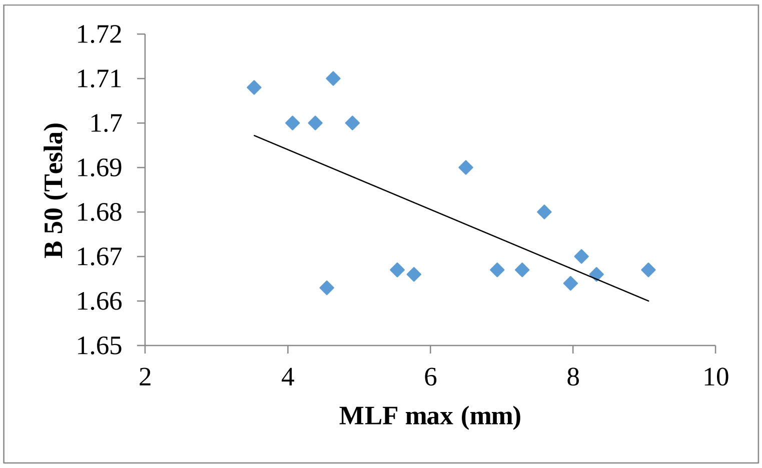


Fig.6 Effect of mould level fluctuation on Permeability

In the present work focus was kept on cleanliness of electrical steel using diffuser. The diffuser in tundish, force the inclusion to float and results in cleaner steel. As tundish is the last vessel where some changes can be done to improve the cleanliness of steel. Hence trials were conducted with diffuser in electrical steel grades to study the inclusion severity and its effect in the final electrical properties.

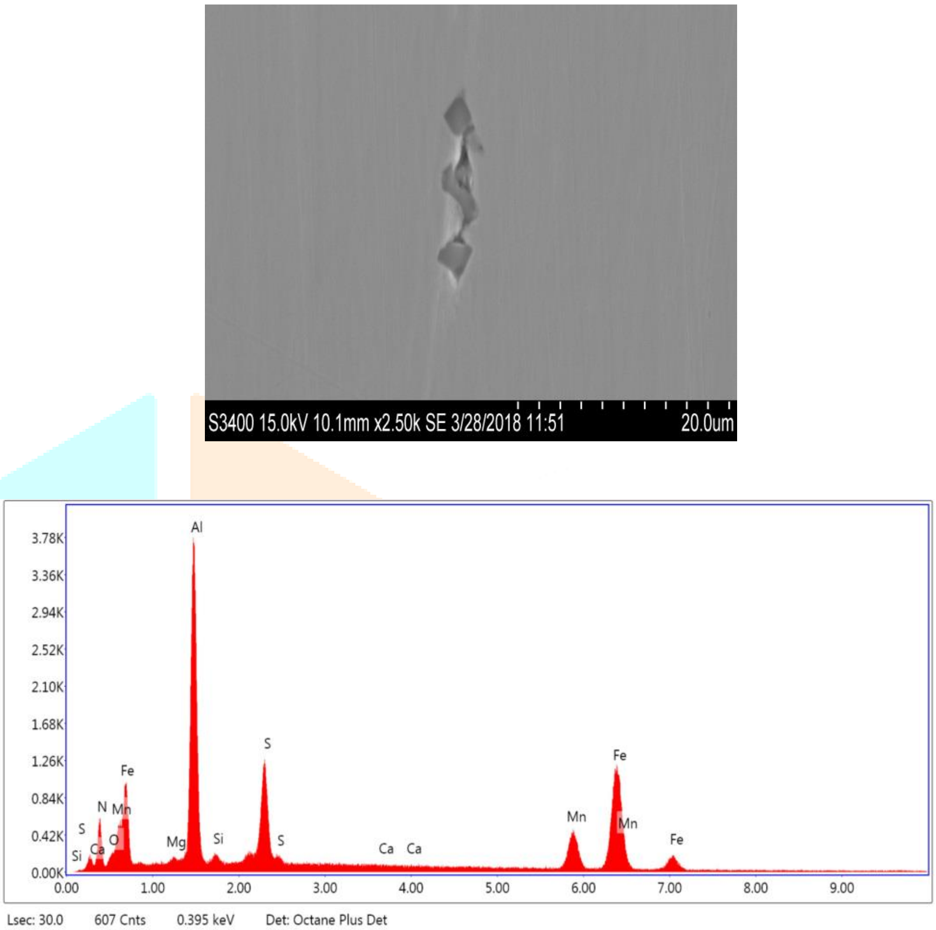


Fig. 7 SEM analysis of inclusions

SEM analysis of non-oriented electrical steel sample was done to check the type of inclusions formed in electrical steel. The EDS analysis can be seen in Fig 7. From the SEM analysis AlN, MnS, FeS, MnO type of inclusions and precipitates were found which mostly comes from in-complete flotation in tundish.

For producing CRNO electrical steels, high purity low sulphur hot metal is brought to basic oxygen furnace for refining. Taking special care, liquid steel is tapped at temperature on the higher side. It is then send to RH degasser where degassing, high purity ferro-alloy additions and optimum temperature is attained and then send for continuous casting. Cast width is up to 1320 mm and thickness is 220 mm. After cooling, slabs are send to hot strip mill where it is converted into strip of thickness up to 6 mm. After that, the coil comes to continuous pickling line where surface oxide layer, dirt, grease etc. are removed. The coil then comes to cold compact mill, where final reduction in thickness is done. Higher Si grades from CPL comes to BAF (Batch Annealing Furnace) and then to CCM (Cold Compact Mill) to achieve the desired property. At CCM thickness is achieved up to 0.5 mm or as per customer requirement. After CCM, the coil comes to annealing cleaning line, (ACL). It is a special line for processing only electrical steels. At ACL the coils are first cleaned and then annealed in a furnace. After this, coating is done as per customer requirement. The coated coils are dried and cured and then inspected before coiling.

3.2 Effect of diffuser on inclusion severity

Inclusion distribution study was made in Hot Rolled and Cold Rolled samples. Comparison of inclusion percentage in bubbling and non-bubbling heats was done. Argon bubbling was started in the empty tundish, before the opening of first ladle of the sequence. This maintains the inert atmosphere in the tundish and avoids the initial re-oxidation and avoids blockage of the bubbling pores due to the initial chilling of the metal [4]. Bubbling was normal and the back pressure was constant during the sequence casting. We continuously monitored the slag layer of tundish and steel superheat to arrest any deviation. Bottom bubbling does not impart any cooling effect, as the residence time of the melt in tundish, between the gas bubbling location and SEN inlet, is very small. No significant change was found in the tundish temperature during casting.

To compare the effect of bubbling and non-bubbling heats, an inclusion distribution study was made. All the samples were evaluated by optical microscope. Collected samples were ground, polished and observed under optical microscope. The size and number of inclusions were recorded in each frame. The hot rolled and cold rolled samples of 50mm2 size is prepared as per ASTM standards [8] , metallographic procedure using a series of polishing papers followed by diamond polishing up to 2 micron diamond paste. An average of 25 images is taken in optical microscope at 100 magnifications so that complete area of the sample is covered. After that threshold of each image is done. Then the area fraction of inclusion is done. Area fraction gives the area occupied by inclusion over total area of frame. The average of each frame is taken. This area fraction of inclusion is converted into inclusion area percentage.

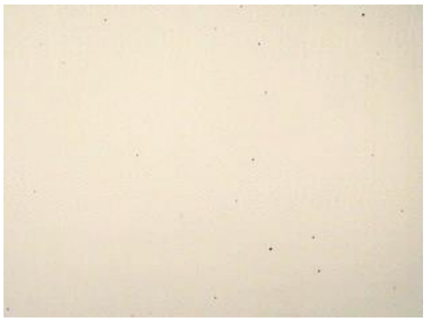
Without Bubbling	With Bubbling
Slab Sample 	Slab Sample 
HR Sample 	HR Sample 
CR Sample 	CR Sample 

Fig.8 Optical micrographs showing inclusion distribution

Table 1 Comparison of Inclusion area percentage with and without diffuser

Inclusion Area %	Without Diffuser	With Diffuser
HR Sample	0.013	0.008
CR Sample	0.012	0.0072

Bubbling argon before the ladle opening in empty tundish has also given improvement in quality and yield of first slab [4]. Additionally, a significant reduction in alumina deposition in submerged entry nozzle has also been observed. There was 35 to 40% reduction in area of inclusions. In the diffuser trial heats, the decrease in percentage of area clogged in SEN was also found. The diffuser trial samples were collected at HR and CR stages. All the samples were evaluated in optical microscope. The size and area occupied by inclusions were observed in each frame. A total of 50 mm2 area was observed in each sample and 25 most severe areas were averaged for comparing the effect. The area occupied by inclusions in each frame was found and adding the area of inclusion in each frame, total area of inclusions in the sample was found. And for better comparison, this area occupied by inclusion was converted into inclusion area percentage. As shown in table 1, the inclusion area percentage in hot rolled and cold rolled coils has reduced up to 40% with the use of diffuser. Also the size of inclusions has reduced from above 10 micron to less than 8 micron in HR sample.

Table 2 Total Oxygen content in steel (ppm)

Heat	**Without diffuser T.O. (ppm)**	**With diffuser T.O. (ppm)**
1	16	12
2	20	15

The total oxygen content of electrical steel sample of two different heats was analysed. From table 2, it can be seen that total oxygen content (ppm) in sample with diffuser is lower than without diffuser. It is known that the total oxygen is indirect measure of the total amount of oxide inclusions in the steel. Thus as total oxygen has reduced with the use of diffuser, it can be said that oxide inclusion has reduced with the application of diffuser. Also the cleanliness of steel has improved.

Table 3 Inclusion Rating with and without Diffuser

Inclusion Type	**Without Diffuser Inclusion Rating**	**With diffuser Inclusion Rating**
B	1.08	0.90
D	1.28	0.95

The severity of inclusions was measured for both the heats, with and without diffuser. Hot rolled sample of electrical steel grade was prepared as per standard. The type and rating of inclusion was done in optical microscope at 100 magnifications. B type (Alumina) and D type (Globular oxide) inclusions were found in both the heats. Inclusion rating of hot rolled sample with and without diffuser was calculated as per standard. The worst 25 frames in each sample were taken and rating was calculated as per rating of inclusions in steel by ASTM standard. It can be seen from table 3 that inclusion rating has improved with the application of diffuser in electrical grade steel.

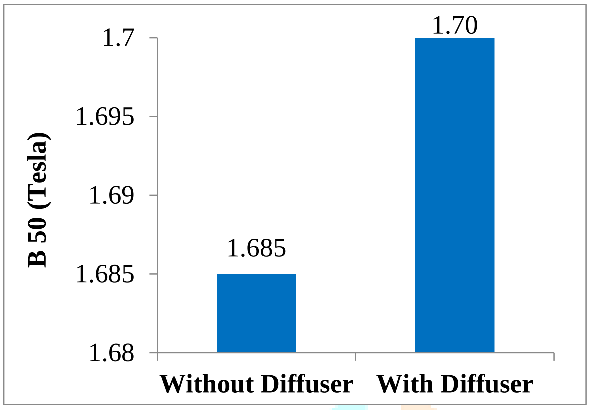


Fig.9 Effect of diffuser on B50

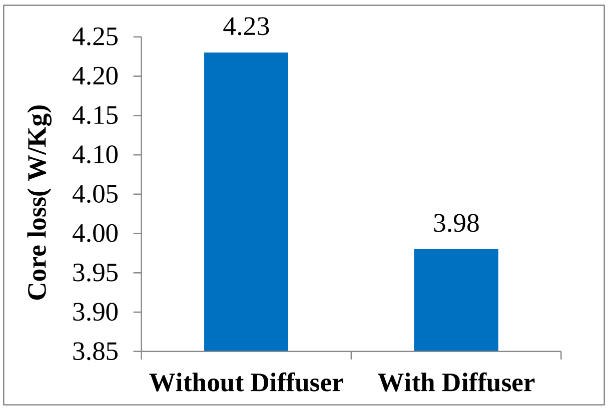


Fig.10 Effect of diffuser on core loss

The magnetic properties like core loss and magnetic induction (B50) are measured in the Epstein frame and single strip tester. Full width of CRNO sample is collected at specific location of coil i.e. ID, OD or Middle. It is ensured that the sample is free from defect such as burr, scratch, dent etc. The sample is prepared in the form of strip of 300*30 mm for Epstein 700 and Epstein 100. The total of 16 strips is taken out of which 8 strips are arranged in rolling direction and remaining 8 are arranged in transverse direction. These samples are inserted in the Epstein equipment in rolling and transverse direction simultaneously. The magnetic property results of trial heats of around 100 coils was found and averaged to compare the improvement with the use of diffuser. As shown in figure 9 and 10 the average magnetic induction (B50) has increased from 1.685 T to 1.7 T and the average core-loss has reduced from 4.23 W/Kg to 3.98 W/Kg with the use of diffuser.

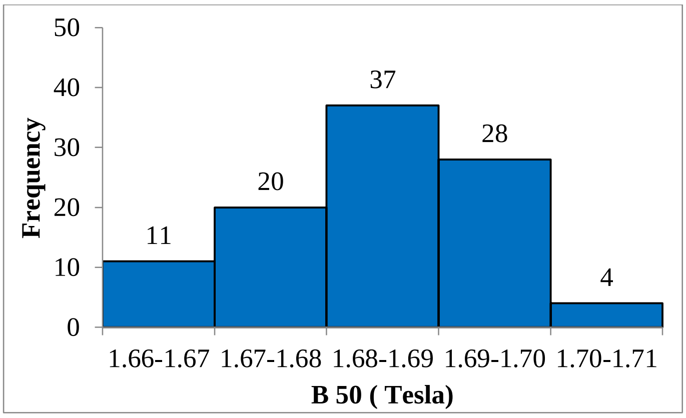


Fig. 11 Distribution of B50 without diffuser

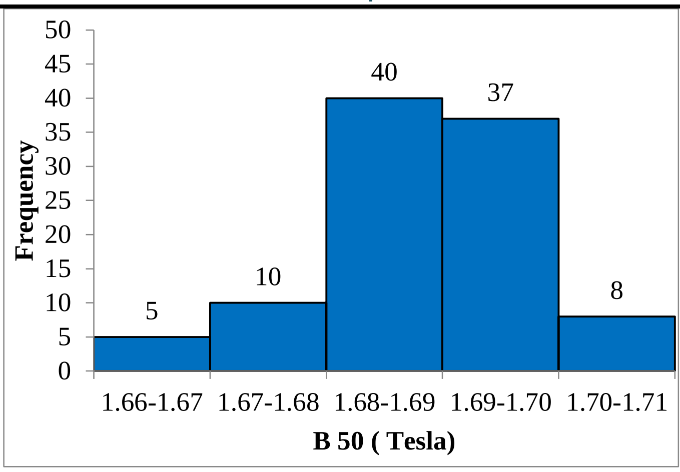


Fig. 12 Distribution of B50 with diffuser

The target value for B50 in 50C600 grade of electrical steel is greater equal to 1.69 Tesla. The comparison of distribution of B50 without and with diffuser has been done as shown in Fig. 11 and 12 respectively. These are the result of 13 heats and more than 100 coils of 50C600 grade of electrical steel. Earlier without the use of diffuser B50 value greater than 1.69 Tesla was 32% and with the use of diffuser B50 value greater than 1.69 Tesla has increased up to 45%. Hence with the use of diffuser the magnetic property results have improved. And the down gradation due to poor magnetic property has been minimized.

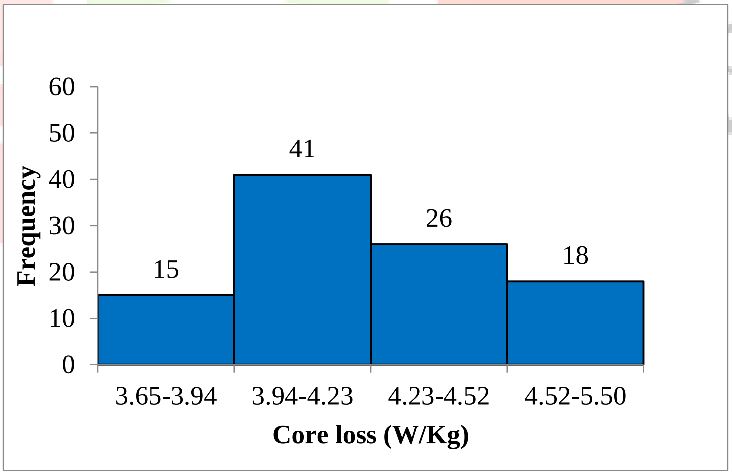


Fig. 13 Distribution of core loss without diffuser

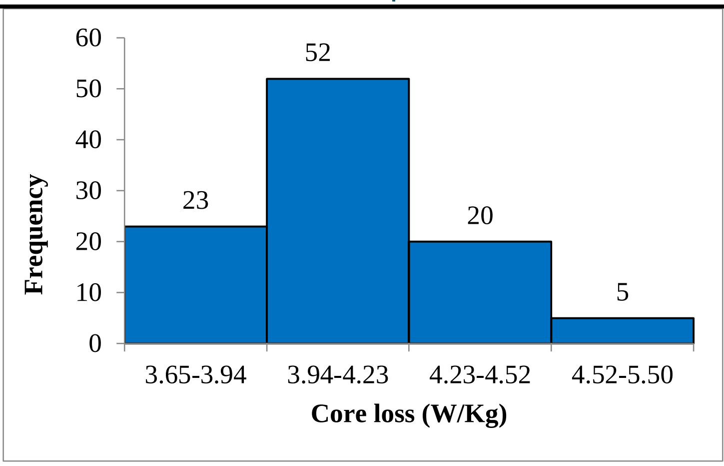


Fig. 14 Distribution of core loss with diffuser

The distribution of core loss without and with diffuser has been shown through Fig. 13 and 14 respectively. For electrical appliances and electric vehicles lower core loss is desired. Without the use of diffuser core loss greater than 4.23 W/Kg was 44% which has come down to 25% with the use of diffuser. Also core loss less than 4.23 W/Kg without the use of diffuser was 56% which has increased up to 75%.

After few successive trials of diffuser in electrical grade steel and seeing good results of magnetic property, it was implemented in other electrical steel grades. The cleanliness of steel in electrical grades has improved. The area fraction of inclusion has reduced by around 40 % in HR coils and the size of inclusions has reduced from above 10 micron to less than 8 micron in HR sample.

The magnetic permeability and core loss results are improved with the application of diffuser. In 50C600 grades of electrical steel having Si from 1.3-1.4 % the permeability has improved and the average value of B50 is 1.70 Tesla and also the watt loss after ageing has improved and the average value is 4.052 W/Kg.

4. CONCLUSION

Core loss and permeability are structure sensitive property and depend on several metallurgical factors with steel cleanliness being one among them. Diffuser has been used to improve steel cleanliness in electrical grade steels to improve its magnetic properties. Plant trials of diffuser were taken in 50C600 grades of electrical steel in a sequence of three heats in slab caster. Inclusion distribution study and comparison of bubbling heats with non- bubbling heats was done. It has been observed that magnetic properties like core loss and B50 value has improved by the use of diffuser. B50 value has increased from the average 1.685 Tesla to 1.7 Tesla and after ageing core loss value has reduced from 4.23 W/Kg and more to 3.98 W/Kg.

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