CRGO Steel - Handle with care

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HISTORY

The earliest process to manufacture Cold Rolled Grain Oriented Electrical Steel, popularly known as CRGO, was first patented 70 years ago in 1933 in USA. The earliest grades of CRGO were known as M10, (approx. 1.00 watts/lb. at 1.5T/60Hz) and M9 (approx.0.90 watts/lb. at 1.5T/60Hz)

By 1947, the first catalogue containing design curves and other essential information on grain oriented steels was published.

In 1955, grades M7 (approx.0.7w/lb at 1.5T/60Hz) and M6 (approx.0.6w/lb at 1.5T/60Hz) were developed and were the most widely used grades of CRGO.

However, the first Conventional Grain Oriented Steel (CGOS) grades known popularly today as M3, M4 and M5 were developed in the late sixties and the Hi-B Grain Oriented Steel grades (HG-OS) were developed in the early seventies whilst laser scribed material in the mid-eighties.

ARMCO, USA, (now known as A.K. Steel) were the pioneers in development of CGOS grades whilst the Japanese mills Nippon Steel and Kawasaki Steel, the pioneers in development of HGO grades and laser scribed grades.

In the development of Grain Oriented Steels over the past 70 years, not only have the hystereses losses been significantly reduced from the earliest grades of GO developed, but the thickness has been significantly reduced, thereby reducing the eddy current losses. The insulation coating has been significantly improved to keep inter-laminar losses at a minimum.

These improvements in GOS have led to an ever increasing demand of this grade of steel which, though being classified as a "steel" is very rarely impacted by the international price movement or other factors influencing mild steels or other categories of steel products. GOS has provided the opportunity to reduce the size of magnetic cores in electrical equipments as also reducing other materials and thereby reducing the cost whilst improving the efficiency of electrical equipments.

There have also been no serious challenges in terms of replacements of GOS for the application in core material in Transformers and there is hardly any new material on the horizon either. Potential challengers like Metglass Amorphous Boron Strip / Mu Metal /Nickel Iron etc. have proven to be not quite useful in replacing GOS due to various technical problems and have already been relegated for use in special purpose applications (mainly high frequency) only in developed countries. That the producers of these materials have tried to dump this technology on developing countries is another matter altogether, which needs to be discussed separately.

Therefore, a comprehensive understanding of GO steels is necessary, especially in the Indian context where CRGO steel is seen from the following perspectives by Transformer Manufacturers (TMs).

A final balancing item in the costing of Transformers. As the competitive pressure on prices of Transformers increases, the only maneuverable "A" class item of significant value is CRGO core, where costs can be reduced. Therefore, TMs are forced to downgrade their core to reduce cost.

A large quantity of seconds, defectives and used GO materials are available, thereby complicating the design and purchase decision further. In fact India is known to be one of the largest markets worldwide, for secondary GOS.

A lack of sufficient information regarding the design parameters, latest materials, nomenclature leading to outdated core designs, which are rarely upgraded or reviewed.

A tendency by SEBs to specify the "best" HGO available and stringent documentation and inspection procedures in a bid to improve the core quality.

In view of the above, this paper attempts to first explain the various terms associated with GO steels, the relevant properties, the best processes for fabrication and the relevant check points and some suggestions and conclusions to ensure better core quality.

TERMS AND DEFINITIONS

AISI - American Iron and Steel Institute which gave the nomenclature for CGO materials with M as a prefix and a number following (eg. M4, M5, M6 etc.) M indicates magnetic material, and the number following approximately indicated 10 times the core loss of earliest CRGO material in watts per lb. at 1.5T and 60 cycles. Today however, this number is not relevant, but still denotes the accepted grade and popularly used throughout the world (e.g. M4 denoted magnetic material having core loss of approx.0.4W/lb at 1.5T/60Hz).

Core Loss: It is the electrical power lost in terms of heat within the core of electrical equipment, when cores are subjected to AC magnetising force. It is composed of several types of losses - Hystereses loss, eddy current loss within individual Laminations and inter-laminar losses that may arise if Laminations are not sufficiently insulated from each other.

Eddy Current Loss: This component of core loss is the energy lost by the circulating current induced in the metal by the variation of magnetic fields in the metal. Therefore, more uniform the magnetic field in the metal, lower the eddy current losses.

Hystereses Loss: The power expended in a magnetic material as a result of the lack of correspondence between the changes in induction resulting from the increase or decrease of magnetising force (which is a result of it being cyclic, i.e. alternating) (explained in detail later on in this paper).

Inter-laminar Loss: The power expended in a stacked or wound core as a result of weak insulation resistance between Laminations resulting in the flow of eddy current within a core, across Lamination sheets.

Surface Insulation Resistance: The resistance of a unit area of surface coating measured perpendicular to the surface usually expressed in ohm-Cm2 per Lamination. Surface insulation resistance is considered adequate if the inter-laminar loss is restricted to less than 2% of total core loss. In absolute values it should be greater than or equal to 10 ohms Cm2 and it is measured by the Franklin test method.

Saturation Induction: The maximum excess of induction possible in given material above that produced in a vacuum by a given magnetising force. It is numerically equal to the maximum induction expressed in gausses minus the magnetising force in Oersteds (B minus H).

Stacking factor: The proportion of steel that would be found when Lamination sheets are stacked on top of each other as compared to a solid steel section for the same volume. It varies between 95% to 97% for CRGO steel coils, however it reduces with fabrication if there are "burrs" developed. This is turn would increase the overall core loss of the electrical equipment. The balance percentage of stacking factor (3 to 5 %) is air!

Burrs: The residual steel on the edge of steel sheet where shearing or punching during fabrication has taken place, thereby increasing the thickness on the edge and reducing the stacking factor. Burrs can be reduced by accurate and precise fabrication and having cutting blades and tools well sharpened at all times. They can also be reduced by deburring and stress relief annealing.

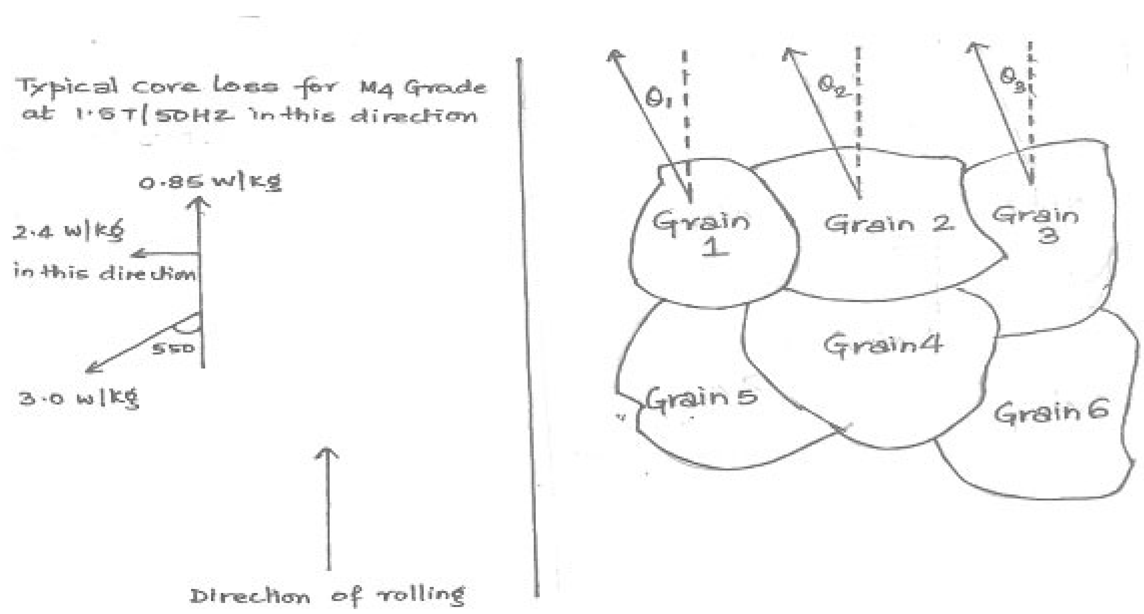
PROPERTIES OF GRAINS, DOMAINS AND UNDERSTANDING OF HYSTERESES LOSSES

Every type of steel has "grains" which consist of "domains". These "domains" are nothing but electrical charges oriented in any random direction. Therefore if a Transformer were to be made of Mild Steel used as core material, the core loss would be approx. 16 to 17 w/kg at 1.5T/50Hz and the size of the Transformer would be approx. 18 to 20 times the size of a Transformer manufactured with GO steels.

The main difference between regular "carbon" steels and GO steels are:

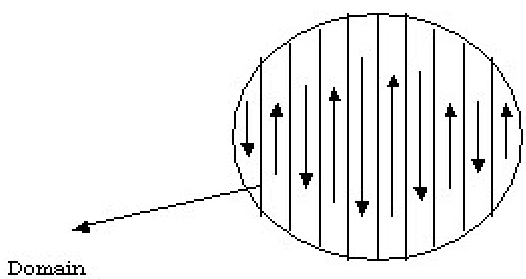
1. The size of the "grains" in GO steels are purposely "grown" and made bigger and are about 10 times the size of the grains in regular steel, thereby reducing the hystereses losses. The size of grains in CGOS is 2 mm to 5mm and HGOS is 5mm to 20mm. In regular steels the size of a grain is less than 0.5mm.
2. The grains in GO steels are all aligned almost parallel to the direction of rolling of the steel (i.e. the length of the steel). The angle of mis-orientation (i.e. deviation from the rolling direction) is maximum 7% for conventional GO and less than 3% for Hi-B GO steels. This reduces the hystereses losses as "switching" (explained later) becomes easier within the domains.
3. The chemical composition of the GO steels has about 3.2% of Silicon as an alloy, thereby increasing the specified volume resistivity of the steel, thereby reducing the eddy currents. GO Steels are also decarbonised and have no more than 0.06% of carbon in their chemical composition, which prevents aeging of the steel.
4. There is a special carlite insulation coating on the steel, which reduces the inter-laminar eddy current losses within the core.

Let us understand how exactly hystereses losses are developed with respect to GO electrical steels: The microstructure of the steel, as mentioned before, consists of numerous "grains" each of which have domains. The magnified diagram would look like this:

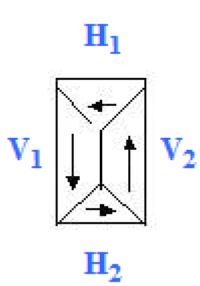


O = Angle of misorientation from Rolling direction Grains which is less than 7% for CGOS and less Than 3% for HGOS

The typical picture inside any "grain" would consist of domains like this:

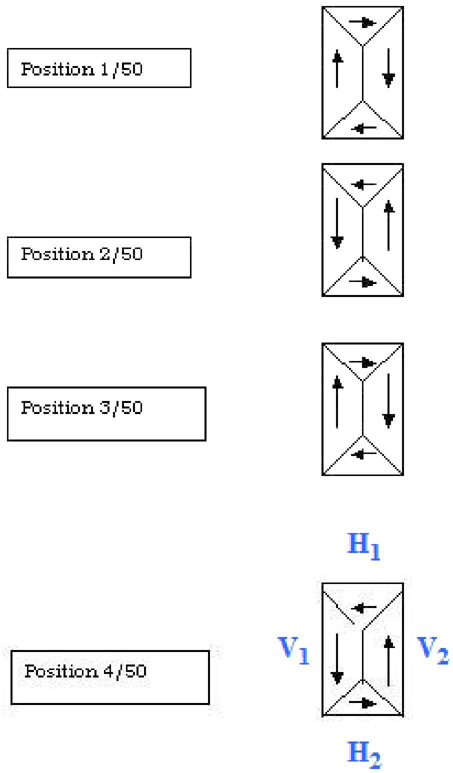


A domain when expanded would look like this:



Thus, every domain is nothing but a closed magnetic circuit as shown in the figure above.

Now consider what happens when an alternating current of 50 cycles is applied. The domains "switch" to and fro 50 times in a second. Therefore the domain looks like this as the current alternates 50 times and the diagrams below represent the direction of the domain as the current alternates.



And so on… 50 times every second

It is relatively very easy for the vertical switches (V1 and V2) to occur but very hard for the horizontal (H1 and H2) switches to occur.

The horizontal switches require more energy to be completed and also "lag" behind the vertical switches, and this results in heat, which results in the hystereses loss within the steel. The sum total of the energy required for the horizontal switches to occur are the total hystereses losses of the steel. Thus the larger the grains, the lower the losses as there are less total number of grains in the steel and therefore less number of "switches" and low hystereses losses.

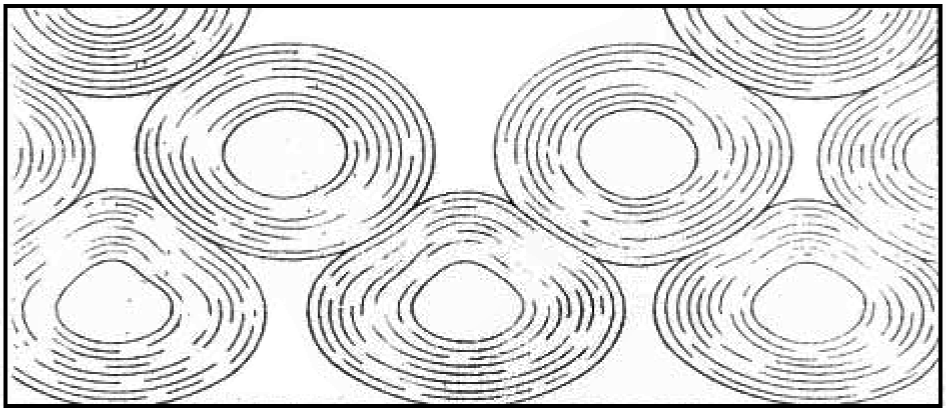
PROCESSING OF CRGO STEEL INTO LAMINATIONS

CRGO steel is a "delicate" steel to be handled with care. As the magnetic property of the steel and not the tensile strength (as is the case with most other steels) is the important quality required, it is imperative that we understand the nuances in handling, storing and processing of this steel. If these are not done properly, it ultimately leads to higher losses and the results are not as per design.

Stresses are of two types, elastic stress and plastic stress. An elastic stress is a temporary stress which any GO steel may be subjected to like some load on top of the coil or a slight force to decoil. The moment the stress is removed, the original magnetic properties of the material are restored and these are no longer damaged.

However, a plastic deformation due to winding into cores or pulling or stretching or bending GOS as shown below, can only be rectified by a stress relief annealing at around 820ºC.

1. Storage of CRGO coils has to be done properly as improper storage may result in excessive stresses unintentionally. This type of stress can be elastic or plastic depending on the severity of the wrong storage and the resulting deformation in coil shape (if any).
2. Improper handling of strip, sheets or long Laminations as shown in the diagram below, can introduce stresses that can distort magnetic properties. These stresses are usually plastic stresses.



UNINTENTIONAL INTRODUCTION OF EXCESSIVE STRESS IN STEEL DURING STORAGE OF COILS

Tests conducted at the plant of M/s. Kryfs Power Component Ltd., Kherdi, on Soken Single Sheet Tester showed a deterioration of 7% in core loss for material that was bent. However after stress relief annealing at 820ºC, the deterioration was only 2% and most of the original magnetic properties (with respect to core loss) of the material were restored.

3. Processing operations like slitting, shearing, notching, holing etc. all damage the grain structure of the GO material around the area of fabrication and working. Most of these induced stresses are plastic stresses that can only be removed by stress relief annealing. To determine the effect of annealing, two stacks of Epstein samples measuring 30mm x 305mm were fabricated from M4 grade CRGO steel coils. Stack 1 was cut and annealed in a fast single sheet roller hearth annealing furnace at a temperature of 820ºC and stack 2 was left unannealed. Both the stacks were sent to ERDA, Vadodra for evaluation of specific core loss and B-H curves. The report is attached in Annexure 1 but the brief results are as under:

	Core loss at 1.5T/50hz(w/kg)	Core loss at 1.7T/50Hz (w/kg)
Stack 1 (annealed)	0.82	1.36
Stack 2 (unanealed)	1.00	1.61
Values as per Mill T.C	0.81	-

This clearly shows that stress relief annealing significantly restores the original magnetic value of the material and removes both elastic and plastic stresses. This is especially true when the width of the strip being worked with is extremely narrow.

4. Burrs are developed during fabrication, which are unavoidable in any steel fabrication operation. Burrs decrease the stacking factor (see the definition of Burrs) In Indian conditions where most of the fabrication processes are performed manually and carbide blades are not used, burrs are easily developed and can

dramatically increase the overall losses of the GO steels. Therefore the Laminations need to be deburred (to reduce / remove the burr) and also stress relief annealed thereafter as it creates an oxide film on the burrs, thereby reducing the conductivity of burr contact and minimising losses.

5. The method of holding the Laminations in a core assembly and the mechanical pressure applied to the core assembly also affects the total core loss. Uninsulated bolts or assembly by welding, would provide a low resistance path and increase eddy current losses and should therefore be avoided. High assembly pressures decrease the surface resistance and increase the inter-laminar losses and increase the total core losses. Therefore excessive clamping on the core must be avoided as the resistance of surface insulation is inversely proportional to the pressure applied. A high clamping pressure leads to breakdown of surface insulation resistivity and higher inter-laminar losses.

6. Inaccurately cut angles in mitred cores also result in a distortion of flux and increase in overall core losses. Air gaps at joints can drastically alter the values of t he total core loss.

7. Variation in thickness in the same width step of material not only results in problems in core building, but also increases the overall core loss of the material as it increases the air gaps during the assembly.

8. Residual material on Lamination surfaces like oil, dust etc. also adversely affects the stacking factor and increases the total core loss.

9. The method of assembly of core, i.e. one piece at a time or two pieces or three pieces also marginally increases or reduces the core loss (lower number of sheets in assembly results in lower core loss).

DESIGN LOSSES VERSUS ACTUAL LOSSES

A regular complaint of Transformer designers is that though individual losses on single sheet tester are within the guaranteed parameters, the total no load core loss of the material on assembled core are not matching the theoretically derived no load losses.

In the light of the above discussions, it is clear that there are various other factors affecting the total no load core loss besides the intrinsic value of the core loss of the GOS material alone.

It must also be mentioned that SOKEN (Japanese) single sheet tester which is mentioned in Nippon Steel Catalogues and is known to display consistent readings and results over a number of years, requires regular calibration which is often ignored. Much cheaper locally (Indian make) versions of the single sheet tester, whilst reliable for non-grain oriented and lower grade of electrical steels are not consistent in their results and cannot be relied upon to provide accurate measurements for Grain Oriented Steels. This observation is made from practical experience.

Further, designers would be well advised to develop their own data on the points mentioned above as there is no universal standard on most of these points and the practices differ with different Transformer Manufacturers.

However, a guideline on dimensional and other tolerances extracted from major international standards from finished Transformer Laminations is given below as a quick reference guide:

ATTRIBUTE	TOLERANCE PERMISSABLE
Length	Upto 315mm) +0/-0.4 mm (From 315mm to 1000 mm) +0/- 0.6mm (From 1000 mm to 2000 mm) +0/- 1 mm (From 2000 mm to 4000 mm) +0/- 1.6mm
Width	Upto 150 mm) +0/- 0.25 mm (From 150 mm to 500 mm) +0/- 0.3 mm (More than 500 mm))/- 0.5mm
Angle	+ / - 5 minutes
Edge Camber	Max.1.5mm in 2000 mm length (as per BS 60 1)
Burr	25 Microns Max. or 10% of thickness, whichever is less
Stacking Factor	95.5% (for M3) 96% (for M4 & M5) 96.5% (for M6) (as per major International standards)
Thickness	+/- 0.03 mm (as per major International standards)
Insulation Resistivity	Min.10 Ohm / sq.Cm. as per Franklin method

GRADES, NOMENCLATURES AND MATERIALS

Different mills have different brand names and nomenclatures whilst producing GOS and HGOS. Many a times this creates confusion in the mind of the customer regarding the exact requirement of the material. Designers use outdated nomenclatures from old catalogues of mills which are no longer valid and this causes some confusion in the material being asked for and supplied by the fabricator.

Most mills have now switched over to the following method of grading Grain Oriented Steels:

(Thickness) (Brand Name) (Core loss at 1.7T/50Hz)

For eg. Nippon Steel grade 23ZH100 means thickness 0.23mm, ZH is the brand name for Hi-B for Nippon Steel and 100 means 1.00W/kg at 1.7T/50Hz.

Similarly 23 RGH100 IS Kawasaki Steel nomenclature for the same material and 23ORSIH100, the Thyssen Krupp Eklectrical St eel (TKES) nomenclature for the same material.

Therefore TMs would be well advised to use these latest nomenclatures whilst specifying GOS requirements to avoid confusion. Even if a TM is looking for a particular core loss at 1.55T or 1.6T, then the GOS which gives the required core loss (these intermediate losses can only be derived from standard core loss curves of mills as no mill guarantees losses at intermediate flux densities) and specify the core loss of the grade of GOS required at 1.7T in the purchase order. Rather than specifying old nomenclatures like MOH, MIH or MZH which are neither precise nor convey adequate information, new nomenclatures conveying precise thickness and core loss information to the fabricator should be used.

Another important question is how to ensure the quantity of the material being used is prime? Many SEBs have initiated stage inspections of material during fabrication of the Laminations to ensure that only Prime material is being used. Though this is a step in the right direction, it is a tedious and time consuming process but due to lack of a better solution at the moment, a generally accepted practice.

One more solution could be for Central Electricity Authority to approve fabricators of Laminations who comply with certain specified quality procedures and methods as "Approved Fabricators" who could be entrusted the work of ensuring the required quality, for certain jobs where quality cannot be compromised.

CONCLUSION

Though the processing of CRGO steels appears to be a simple engineering activity of fabrication of steel into desired shapes as per the design provided, in reality it is one of the most demanding and precision jobs in the engineering industry. Therefore, it is imperative that TM have the basic knowledge of this delicately important raw material which forms the core of their Transformer. The information provided in this paper attempts to provide this basic foundation.