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Study of Customized Cold Rolled & Drawing Quality of Steel

Smeeta Kujur, Santosh Kumar, K.K. Singh
Research & Development Centre for Iron & Steel
Steel Authority of India Limited,
Ranchi-834002, Jharkhand, India

ABSTRACT
Low Carbon Drawing Quality steel with enhanced Si and P contents is gaining popularity for making lamination cores of fractional horsepower motors for economic reasons. The steel contains smaller quantity of silicon than non-oriented electrical steels. It is required to keep the carbon content and other impurities as low as possible to enhance magnetic properties, and increase the phosphorus to increase the hardness and brittleness to facilitate punching during lamination core making. Further, in order to avoid the detrimental effects of aluminum nitride on grain growth and magnetic properties, low carbon electrical steel is often killed with silicon instead of aluminium.Cold Rolled (CR) coils of customised CR2D (Si-Killed) steel grade have successfully been developed for electrical stamping applications. The steel was made with C: 0.05% and Si: 0.25-0.30%. The continuous cast slabs were hot rolled to 2.5-3.0 mm thicknesses which were subsequently cold rolled to 0.5 mm coils. The CR coils were batch annealed at hot and cold spot temperature of 690-700°C & 650-670°C, respectively. The CR coils were further subjected to skin pass rolling. The product was characterised for the required properties which were found to be satisfactory for the intended applications. The semi processed stamping grade of steel, so developed, has been satisfactorily used for making lamination cores for fractional horsepower motors owing to less than 10 W/kg of iron loss values at 50 Hz, 1.5 T alongside the suitable mechanical properties in terms of YS (180-220 MPa), UTS (300-370 MPa) & Elongation % (30-35) which exhibits excellent punching ability for making these motor lamination cores.

Keywords**:** Cold Rolled, Core Loss, Hot Rolled, Annealing, Recrystallization, Grain growth

INTRODUCTION

IS 513 CR2D steel with (Si 0.03% max) is already under regular production at Bokaro Steel Plant. In present market scenario, CR2D grade with high (Si 0.25-0.28%) is in high demand for electrical stamping applications with good electrical properties, especially core loss value. In order to obtain a combination of mechanical and electrical properties the process parameters need to be carefully controlled. Considering the above requirements, efforts are made by to develop customized cold rolled CR2D grade with minimum core loss.

LITERATURE REVIEW

Electrical steels

An electric motor is composed of a stator and a rotor. The stator is composed of wire made of high conductivity material e.g. copper. The stator wire carries the magnetizing current and it is wound on the rotor (rotating core). The core is generally made in laminated form typically using high silicon steel sheets. The steel used in the core should possess good magnetic properties like (a) low core loss and (b) high permeability. Core loss is the loss of power in the form of heat in the rotor during the running of the motor [1]. Permeability is the ability of the rotor material to acquire high magnetic induction at a given magnetic field for a given volume of the rotor. Generally, low core loss and high permeability are desirable properties of the steel sheets used in the rotor [2]. For large electric motors low watt-loss is desirable as these are more difficult to cool compared to smaller motors. For small motors permeability is more important in order to reduce the size of the motor. Hence for rotors of smaller motors, high permeability combined with moderate watt loss and low cost is highly desirable. Generally, 0.4 to 3.5% silicon is added to electrical steels. Silicon reduces core-loss in steel but it decreases the permeability or saturation induction of the steel [3]. Also, high silicon steels are costly due to higher alloying additions and higher processing cost. Decreasing the silicon content in the steel is expected to reduce the overall cost of the rotor in addition to imparting higher permeability.

Electrical steels in the form of sheets and strips constitute essential components in electrical equipment used for generation, distribution and utilization of electrical energy [4]. In AC appliances such as transformer, motor and generators, it is necessary to utilize core material or lamination, which possesses high permeability and low core loss. Based on crystallographic texture and resulting magnetic properties, electrical steel strips are classified into two types (i) Cold Rolled Non Oriented (CRNO) electrical steel (ii) Cold Rolled Grain Oriented (CRGO) electric steel. Non-oriented electrical steel has a crystallographic texture containing almost all-possible orientations (random orientation) distributed within the grains resulting in same magnetic properties in all directions. These are essentially required in the cores of rotating electrical machines like motors and generators where the magnetic flux has to flow

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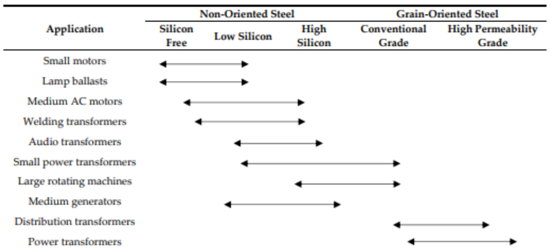
in all directions along its path. CRNO electrical steels can be supplied as (i) Fully Processed (FP) strips (ii) Semi Processed (SP) strips. In case of fully processed material, final magnetic properties are achieved through annealing at the supplies / steel producers' end and can be readily used by the equipment manufacturer for punching laminations. Semi-processed electrical steels are increasingly being used replacing conventional fully processed CRNO due to their cost effectiveness. These materials need decarburization annealing treatment at customers' end for developing final magnetic properties. Semi processed electrical steels are finished to the final thickness by the steel producer / supplier and final magnetic properties in the punched lamination are achieved though decarburization annealing / stress relief annealing at the customers' end. Semi processed coils are generally temper rolled after cold rolling and annealing to improve punchability, to facilitate strain induced grain growth during decarburization annealing and to obtain desired amount of surface roughness to prevent sticking of the lamination during decarburization annealing[5]. Semi-processed silicon bearing steel is well established due to favourable magnetic permeability effect on core loss properties but, due to higher alloying content, it affects the permeability of the steel sheet, thus reducing the scope for its application in small motor & rotor component[6].

Table 1. Application of commercial electrical steel



In the present invention it is aimed to develop steel with low amount of Si by selecting a suitable chemistry and process parameters resulting in a combination of moderate watt loss with high permeability as required by application to smaller and medium sized motors. This is because smaller motors are easier to cool after service than larger motors and smaller motors are generally used intermittently.

Chemistry of electrical steels

The chemistry of electrical steel was selected based on the magnetic and mechanical properties. Alloying additions are generally made to increase the electrical resistivity of the material and thus to decrease the eddy current component of the core loss[7]. The addition of silicon to electrical steel decreases the coercive force (He), thereby reducing the hysteresis loss. It also increases the electrical resistivity and thus decreases the eddy current loss. In conventional non-oriented steel, it is used in the range of > 0.4% depending on the end-use, however, in the present invention, the chemistry was selected with Si decreasing the eddy current loss[8,9,10]. It improved the mechanical properties and hence improved punchability. Carbon in the form of Fe_3C is detrimental for magnetic properties as it increases the core loss. Also, carbon held in solution during cooling after annealing leads to precipitation of carbides during service over a long period of time resulting into increase in watt loss[11,12]. This phenomenon is known as magnetic ageing[13]. Thus for best magnetic behaviour of the material, carbon in the lamination preferably should not exceed the level of 30 ppm after decarburisation annealing.

Process route

Cold rolled sheet of 0.5 mm were commercially processed through LD(Linz-Donawitz))-Slab caster - hot strip rolling – cold rolling - batch annealing - temper rolling. The steel was continuously cast in 210 mm thick slabs. The slabs were charged in reheating furnace and rolled to 2.3 mm to 1 mm thickness with proper hot rolling parameters. After cold rolling to 0.5 mm thick, the steel sheet was annealed in Batch Annealed Furnace (BAF) at 560 - 700°C followed by appropriate amount of temper rolling (6-9%) to achieve the required hardness and roughness in the steel sheet products. The process route for low carbon low silicon steel shown in Fig 1.

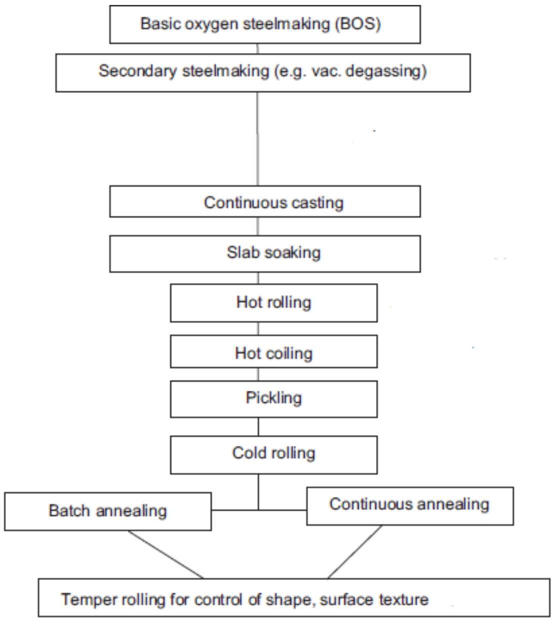


Fig1. Schematic representation of process route for low carbon low Silicon steel

Hot Rolling

Two hot strips of electrical steels were taken and different cooling strategies were introduced, they both revealed different microstructure and texture. The finishing temperature as well as the cooling conditions after the last hot rolling pass affects the hot strip microstructure significantly in electrical steels [14]. A low finishing temperature in combination with water quenching after hot rolling lead to a deformed state with small grains (mean lineal intercept length of 6 µm) near the surface and a banded structure with flat elongated grains in the mid layer, whereas a furnace cooling after hot rolling results in a fully

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recrystallized, more homogeneous microstructure across the strip thickness with a mean grain size of 46 µm near the surface and 100 µm in the mid layer. For hot strip in quenched state, a narrow grain size distribution with few grains larger than 30 µm was obtained and for the grain size distributions of the recrystallized microstructure of hot strip the grains in the mid layer was about twice the size of the grains near the surface.

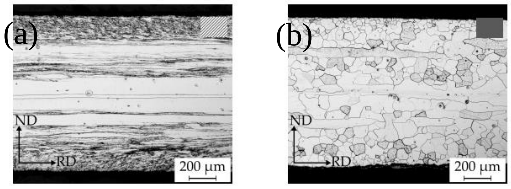

Fig 2. RD –ND micrographs of (a) Hot strip after water quenching (b) hot strip after furnace cooling

Cold Rolling

Cold rolling defines the final thickness and increases the driving force for recrystallization during final annealing. This driving force is directly coupled to deformation and the stored energy [15].Because of this, apart from the hot strip state (Quenched or Furnace cooled), the cold rolling reduction also influences the grain size and texture evolution. The micrographs of two investigated cold strips are shown in Figure 3.

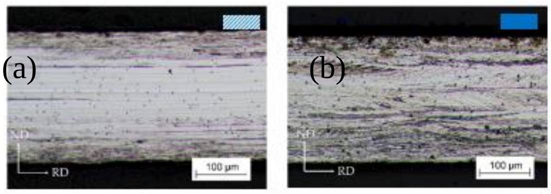

Fig 3. Micrographs of cold rolled strips (a) Quenched (b) Furnace cooled

After cold rolling, elongated grains and a banded structure were present in both cases. For quenched structure, the dominant band in the mid layer of the hot strip was preserved during cold rolling. As can be seen in the micrograph in Figure 3a, only horizontal grain boundaries between different bands were visible by optical light microscopy. Related investigations by EBSD measurements [16] showed the absence of grain boundaries in such banded structures and therefore these areas are assumed to possess a low stored energy. In contrast, after cold rolling of hot strip after furnace cooled, the initial grains were still visible but strongly elongated with deformation bands in most grains, Figure 3b.

Final Annealing

The annealing process determines both the final grain size and texture via recovery, recrystallization, and grain growth. Out of all annealing parameters, the temperature has the strongest influence on the grain size and texture development. The effect of annealing temperature on cold rolled strips is shown in Fig 3.

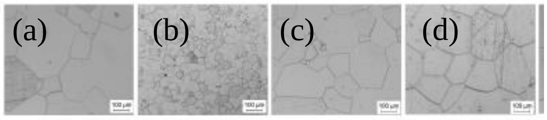

Fig 3. Micrographs of annealed strips (a) Quenched strips - 1000 ^{0}C (b) Furnace cooled strips -900 ^{0}C (c) Furnace cooled strips - 1000 ^{0}C (d) Furnace cooled strips - 1100 ^{0}C

The grain size is an important factor as it decreases hysteresis losses while increasing excess losses [17]. Thus, the optimal grain size is always application dependent. At low frequencies (wind turbine), the hysteresis losses are dominant, thus a large grain size is needed and at higher frequencies (electric vehicle engines), the excess losses can get quite big, requiring a smaller grain size. Therefore, it is necessary to achieve a magnetic preferable texture with ND-cube components in combination with a grain size matching the application.

It was found that cold-rolled reduction ratio and annealing temperature are the predominant factors influencing the core loss. Annealing temperature decreases the core loss through combining effects of coarsening grain size and development of good texture. Cold-rolled reduction ratio is detrimental to the core loss through the combined effects of refinement of the grain size and development of poor texture.

EXPERIMENTAL

The heat of Cr2 D steel was made in 300 t converter at BSL. The chemical composition of the heats was determined by M/s Bruker make Q8 Magellan 3440 model Optical Emission Spectrometer and the results are shown in Table 1.

Table 1: Chemical compositions of CR2D steels (wt.%)

Steel	**C**	**Si**	**Mn**	**Al**	**S**	**P**
H 1	0.08	0.236	0.26	0.009	0.008	0.025
H 2	0.08	0.256	0.22	0.006	0.009	0.013

Carbon increases the core loss through refinement of grain size and the amount of cementite. Phosphorus increases the core loss through both refinement of the grain size and development of a poor texture. Silicon improves the core loss through the development of a good texture and increasing resistivity.

The heat was made with combined blow technology and the tapping temperature 1660-1680 ^{0}C. The liquidus temperature at the caster was 1531 ^{0}C and it was continuously cast into slabs at a casting speed of 1.1 m/min. All slabs were hot rolled to 3 mm thickness keeping the finishing temperature 880± 15^{o}C and coiling temperature was 680±15^{o}C. Samples of hot rolled coils were cold rolled in Experimental Rolling Mill at RDCIS with varying reductions of 65% and 75%. During Batch annealing in plant conditions, due to their large mass, the cold rolled strips experience very slow cooling and heating rates. The sheets were annealed at 690^{o}C for 24

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hrs and 32 hrs with slow heating rate of 1 ^{0}C/min. The same batch annealing conditions were simulated in muffle furnace of the laboratory for the study after cold rolling.

For light microscopy, specimens of were cut Cr2D sheets and ground successively from 100 to 1200 grit using water proof silicon carbide paper and finally polished by using alumina suspension of particle sizes 1.0 μm and 0.3 μm. An optical microscope (Model: Olympus GX 71) was used for microstructural examination after etching the specimens in 2% Nital solution (98% alcohol + 2% nitric acid).

Core loss testing is performed by single sheet iron loss tester RK-45. It is provided with a stroboscopic probe when placed on specimen, closes the magnetic path between probe and specimen. Probe has two coils one is primary and second is secondary (like transformer). When power applied to primary coil and detected by secondary coil appropriate to specimen data and measure voltage, current and power. Then measured data calculated by microcontroller appropriate to specimen's data (core area and weight) and directly displayed Watt/Kg on LCD

RESULTS AND DISCUSSION

Alloy Design and Hot Rolled Microstructure

Motor laminations are produced by using electrical steel lamination. The addition of silicon eases the penetration of magnetic fields, increases its electrical resistance, and decreases the hysteresis loss of the steel. Steel with silicon is used in numerous electrical applications where electromagnetic fields are essential, such as electrical stators/rotors and motors. Figure 4.shows the phase diagram develoved from software ThermoCalc. Figure 5a.shows the hot rolled structures. Figure 5b. shows the air cooled structures.

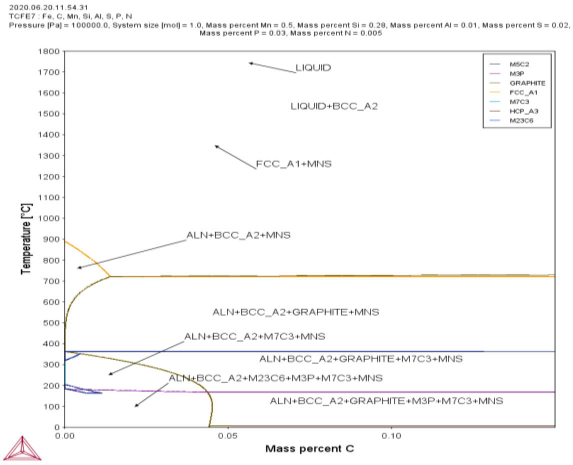

Fig.4 Phase Diagram of CR2D steels(ThermoCalc)

Though the silicon can help in reducing corrosion, the main reason to add silicon is to decrease the steel's hysteresis. Hysteresis is the delay between the times when a magnetic field is first produced or joined to the steel and when the field fully develops. The added silicon makes the steel more effective and faster at building and maintaining magnetic fields. This means that steel with Silicon improves the efficiency of any device using steel as a magnetic core material. Metal stamping is one procedure used to create motor laminations for different applications.

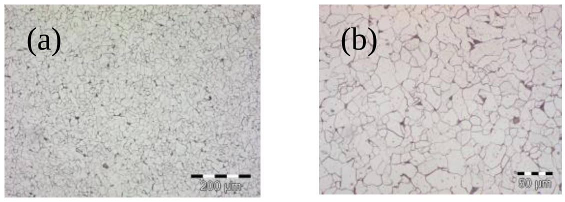

Fig.5 Optical photomicrographs after hot-rolling and air-cooling of CR2D steels

COLD ROLLED AND ANNEALED MICROSTRUCTURE

The cold reduction has an important role in dictating the grain morphology after annealing, texture and mechanical properties. Thus, an optimized cold reduction must be taken into account while high deep drawability. Figures 6a -6b depict the effect of cold reduction on grain size for steel 1. The average grain size of steel 2 which was cold reduced at 75% was 50 μm whereas the steel 1 at the same reduction had the average grain size of 35 μm. More elongated grains were observed at 75% cold reduction than at 65% reduction. Figures 7a -7b show the effect of annealing temperature.

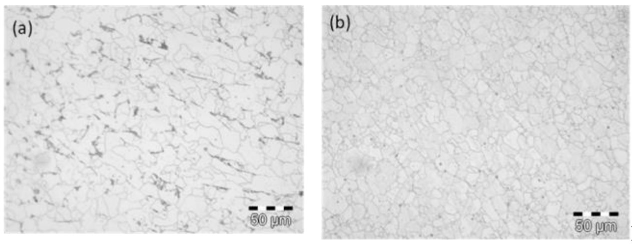

Fig.6 Optical micrographs of CR2 D after annealing at 690 0C (a) 65% reduction (b) 75% reduction

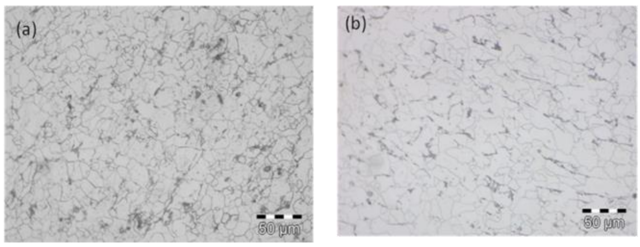

Fig.7 Optical micrographs after 75% reduction of CR2 D steel (a) annealing at 650 0C (b) annealing at 690 0C

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Annealing temperature reduces the core loss through the effect of coarsening the grain size. Average grain size in the cold rolled and annealed coils with annealing temperature of 690 °C is ~ 40 microns whereas the grain size in the annealing temperature of 650 °C is ~25 microns which has led to an decrease in core loss in later. Figures 8a -8b depicts the effect of annealing time on Cr2D grade steels.

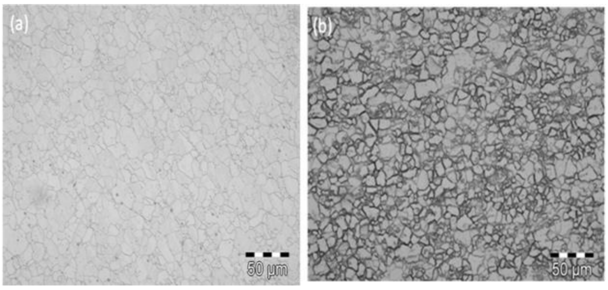

Fig.8 Optical photomicrographs after cold rolling and annealing at 690 0C (a) Annealing time at 32 hrs and (b) Annealing time at 24 hrs

Mechanical Properties

Table 2 indicates that the percentage elongation and r bar has improved in case cold rolled and annealed CR2D steel.

Table 2: Mechanical properties of CR2D steels

S.No	Sample	Yield strength (in MPa)	Tensile strength (in MPa)	Elongation	r-bar
1	H1	200-236	350-370	30-34%	1.39
2	H2	193-236	343-370	30%	1.39

Electrical Property

Table 3 indicates core loss value of cold rolled and annealed CR2D steel

S.No	Cold rolled and annealed sample	Core loss at 1.5 T, 50 Hz
1	Annealing temp - 650 ^{0}C	12-13
	Annealing temp - 690 ^{0}C	10-11
2	Annealing time – 24hrs	12-13
	Annealing time – 32 hrs	9-11

CONCLUSIONS

1. The chemical composition and process variables have significant effect on core loss of CR2 D steel.
2. Carbon, Silicon content, cold-rolled reduction ratio and annealing temperature are the predominant factors influencing the core loss. Carbon increases the core loss through refinement of grain size and the amount of cementite. Silicon improves the core loss through the development of a good texture and increasing resistivity.
3. Vey high cold-rolled reduction ratio is detrimental to the core loss through the combined effects of refinement of the grain size and development of poor texture. But the optimum cold reduction ratio was found to 75% reduction.
4. Annealing temperature reduces the core loss through the effect of coarsening the grain size.
5. Average grain size in the cold rolled and annealed coils with annealing temperature of 690 ^{0}C is ~ 40 microns whereas the grain size in the annealing temperature of 650 ^{0}C is ~25 microns which has led to an decrease in core loss in later.
6. There was significant improvement in core loss when the annealing time increased from 24 hrs to 32 hrs.

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