A brief overview of available Permanent Magnet materials including Alnico, ferrites (ceramics), SmCo and NdFeB will be given. The advantages of each material will be given in terms of properties, stability, corrosion resistance and price. Recent work on magnetising and pulsed magnetic fields will be discussed.
Overview of Nd-Fe-B Magnet Technology and Applications

Dr. Hitoshi Yamamoto\(^{(1)}\) and Dr. Naoyuki Ishigaki\(^{(2)}\)

\(^{(1)}\) Sumitomo Special Metals America, Inc.
\(^{(2)}\) Sumitomo Special Metals Co., Ltd.

Recent development of Nd-Fe-B sintered magnets is over-reviewed, including improved temperature properties, long-time stability, radiation stability and advanced coating technologies. The newly developed Nd-Fe-B /Fe-B base nano-composite material is introduced as a promising candidate of conventional Nd bonded magnets. This material has outstanding features of high remanence, low rare earth content, and relatively high corrosion resistance.

Nd-Fe-B sintered magnets are expanding in various application areas such HEV (Hybrid Electric Vehicles), EPS (Electric Power Steerings), various IPM (Interior Permanent Magnet) motors, robotics, linear motors, transportation train motors and wind-mills as well as already-in-market area of VCM (Voice Coil Motors), MRI (Magnetic Resonance Imaging) and vibration motors of cellular phones. These new emerging applications are over-viewed, and key technologies are emphasized.

The 4.4 Tesla high magnetic circuit using Nd-Fe-B magnets with Halbach structure is mentioned, which has the highest magnetic field ever achieved using permanent magnets. Newly developed portable MRI system for partial-body diagnostics use is referred. The high energy-loss performance of flywheel energy storage system with superconductive materials combined with Nd-Fe-B magnets is also briefly introduced. Improvement of neutron radiation toughness of Nd-Fe-B magnets for undulator/wiggler of synchrotron radiation is referred, comparing with conventional SmCo magnets.
Overview and New Rare-Earth Permanent Magnet Applications in the Automotive Industry

Dr. Bernd Grieb

Magnequench International Inc. Europe

The presentation gives an overview on the use of permanent magnets in automotive. Volumes are increasing tremendously and billions of magnets are used in sensor, motor and actuator applications. Beside basic technical solutions well known since decades new applications are mainly focused on economy, safety and comfort. Different sintered materials like NdFeB and Ferrite are in competition with plastic bonded types based on these compounds. Advantages and disadvantages in cost and technology can be shown in principal and in concrete applications by direct comparison. Examples of new solutions to improve efficiency and security can be shown.
Progress in commercial Nd-Fe-B magnets and innovative applications

Bernd Schleede

Vacuumschmelze GmbH & Co. KG

The paper will cover the following topics:

- improved temperature and corrosion stability of sintered Nd-Fe-B magnets,
- high maximum energy densities,
- innovative applications.
New Nanocomposite Rare Earth Magnets

Don Lee and Sam Liu

University of Dayton Magnetics Laboratory, 300 College Park, Dayton, OH 45469, USA

New, bulk, isotropic and anisotropic nanocomposite rare earth magnets with full density have been successfully synthesized using melt spinning, rapid hot press, and hot deformation. The rapid hot press, including heating and cooling, lasts for only ∼2 minutes, which effectively avoids grain growth. Further hot deformation of the hot-pressed isotropic magnets leads to the formation of crystallographic texture and anisotropic nanocomposite magnets. The magnetic properties and other characteristics of these new nanocomposite magnets are listed below.

(1) (Nd,Pr,Dy)$_2$(Fe,Co)$_{14}$B/$\alpha$-Fe anisotropic nanocomposite magnets
For anisotropic nanocomposite magnets the (BH)$_{\text{max}}$ of 45 MGOe has been obtained in magnets with the rare earth content of 11.6 at%. The $B_r$ and $M_{\text{Hc}}$ are 14 kG and 12 kOe, respectively. The magnetic performance of the best anisotropic nanocomposite magnets is 14 – 37% higher than the commercial die-upset magnets, while their rare earth content is about 15% lower than their commercial counterpart. Anisotropic nanocomposite magnets with much higher (BH)$_{\text{max}}$ are anticipated with further development.

(2) (Nd,Pr,Dy)$_2$(Fe,Co)$_{14}$B/$\alpha$-Fe isotropic nanocomposite magnets
In their current development stage, the isotropic nanocomposite magnets seem to have more commercial significance. Two types of isotropic nanocomposite magnets have been developed: high-(BH)$_{\text{max}}$ magnets and low-rare-earth magnets. The (BH)$_{\text{max}}$ of high-(BH)$_{\text{max}}$ magnets has reached 20 MGOe, or more than 30% higher than the commercial hot-pressed magnets, while the rare earth content is 20% lower than their commercial counterpart. For the low-rare-earth magnets, the (BH)$_{\text{max}}$ ranges 12 - 15 MGOe, while their rare earth content can be up to 65% lower than the commercial magnets. Because of their low rare earth contents, these magnets will have low cost, good corrosion resistance, and improved fracture toughness.

(3) Nanocomposite Nd$_2$Fe$_{14}$B/Sm$_2$(Co,Fe)$_{17}$ magnets
Anisotropic nanocomposite Nd$_2$Fe$_{14}$B/Sm$_2$(Co,Fe)$_{17}$ magnets have been developed to fill the wide thermal stability gap between the Nd-Fe-B and Sm-Co based magnets. Using melt spinning, rapid hot press, and hot deformation, all technical difficulties encountered in a previous attempt to make conventional Nd$_{14}$Fe$_{80}$B$_6$/Sm(Co,Fe,Cu,Zr)$_{7.4}$ type magnets, such as incompatible processes and interdiffusion at elevated temperature, can be overcome. This new type of nanocomposite magnet materials is still in its early development phase. The best (BH)$_{\text{max}}$ obtained so far is 28 MGOe in a magnet consisting of 80 wt% Nd$_2$Fe$_{14}$B and 20 wt% Sm$_2$(Co,Fe)$_{17}$.

It is anticipated that these new nanocomposite rare earth magnets will be in a very favorable position to compete not only with the commercial hot-pressed and hot-deformed Nd-Fe-B magnets that own very small market shares, but also with the commercial sintered and bonded Nd-Fe-B magnets.
Composite Stators for Large Alternators

P. Beckley, H. J. Stanbury, M. Lindenmo

Cogent Power Ltd., Orb Works, P.O Box 30, Newport, South Wales, NP19 0XT, U.K.

The designers of large alternators and motors which have a stator core diameter in excess of one metre must construct the core from segments of steel able to be cut from electrical steel of available width. A choice can be made between grain oriented and non-oriented steel. If grain oriented steel is chosen for stator segments it is usual for the rolling direction (best magnetic properties) to be exploited in the direction of tooth length. Unfortunately, this means that the flux in the back iron is carried by the unfavourable transverse direction of grain oriented steel. Losses in the back iron can be reduced by greatly increasing its depth so that working inductions are lowered, but this greatly increases the amount of steel used. If non-oriented steel is used the special benefits of grain orientation are not available at all.[1]. At present non oriented steel frequently offers an optimal technical and economic solution. Cogent Power has developed a system of composite stators in which both tooth length and back iron use the high permeability rolling direction of the steel. Such a scheme uses a tooth pattern in which a long tooth has a ‘fir tree’ root engagement with the back iron portion of the segment. A series of laboratory measurements have been made using simulated stator structures in which power loss and specific apparent power have been measured. In general the benefits of reduced losses have been very large, eg 40% reduction as compared to the use of non oriented steel or non-composite grain oriented components. Particularly in the case where long teeth are dictated by the need for heavy conductor insulation the benefits of enhanced tooth permeability are very useful. Figure 1 shows an outline of one of the tooth rooting shapes used. Patents have been applied for in relation to the structures concerned and funding sought for a wider programme of prototype construction. The paper to be presented gives data and details of the arrangements which have been quantitatively analysed.


Figure 1
Tooth root shape
Grain-oriented electrical steel sheet JGE without forsterite (Mg2SiO4) undercoat is newly developed. Since JGE has no hard coat such as forsterite, the lifetime of stamping dies used is about ten times longer than in use of conventional grain-oriented steel sheet. The iron loss at the area between teeth and yoke of motor core is remarkably reduced using JGE. Therefore, the maximum motor efficiency of the segmented core motor using JGE is higher than that of non-oriented steel sheet of the highest grade. From these results, JGE is a favorable material for the application to the segmented core motor.
Electrical Steel Sheets and Manufacturing Technique for High Efficient Motors

H. Mogi, C. Kaido, T. Wakisaka, N. Suzuki, Y. Kurosaki, M. Yabumoto, and T. Kubota

Nippon Steel Corporation, Steel Research Laboratories, 20-1, Shintomi, Futtsu, Chiba, Japan

Electrical steel sheets are used for high efficient motor cores in such as an electrical vehicle (HEV/EV) and an air compressor, which are affected by the magnetic properties. In order to make the motors downsized, light, powerful and efficient, the electrical steel sheets have been improved year by year.

In this paper a high tensile strength electrical sheet is introduced for high-speed rotor material, and a thin gauge electrical steel sheet is introduced for low loss core material. Since the magnetic properties are deteriorated by punching and interlocking, these manufacturing influences are examined. The deterioration caused by punching is observed by the domain patterns near the sheared area with a scanning electron microscope, and short circuit loss is evaluated by measurement of inter-laminar resistance and calculation of induction.
Advances on the Characterization of Electrical Steel with Si- and Al-Concentration Gradients

T. Ros-Yáñez (1), J. Barros (1), M. De Wulf (2), L. Dupré (3) and Y. Houbaert (1)

(1) Ghent University, Department of Metallurgy and Materials Science, Gent, Belgium
(2) Arcelor Research Center OCAS, Zelzate, Belgium
(3) Dept. Electrical Energy, Systems and Automation, Sint-Pietersnieuwstraat 41, Gent, Belgium

Electrical steels with high silicon content (up to 6.5wt%Si) are difficult to process by conventional metallurgical routes: ordering phenomena make the material too brittle to be cold rolled. A hot dipping and diffusion annealing process appears to be an alternative production route to obtain steel with a high silicon and aluminium content avoiding rolling problems. Surface alloying with Si and Al is achieved on a conventional steel substrate by hot dipping in a hypereutectic Al-Si-bath followed by a diffusion annealing treatment. The diffusion annealing allows the homogenisation of the composition obtaining a homogeneous concentration of 6.5% Si over the thickness depending on the temperature and annealing time necessary for the diffusion of the elements present in the coating. The alloying elements can also be distributed in a controlled non-uniform way over the thickness of the sheet, creating a concentration gradient. Series of different concentration profiles have been produced and the magnetic properties were measured. A short immersion is sufficient to form a Si-Al-enriched layer with D03 ordered structure (25 at-% Si-Al) in the steel surface: 15 µm of D03-layer is obtained after 20 sec immersion (dependent on substrate and experimental conditions). A short diffusion annealing lowers and broadens this level, e.g. to a “classical” level of 6.5 m-% of Si, while the center of the steel remains at the original level (e.g. 3 m-% Si). Similar gradients are obtained with the simultaneous presence of Si and Al. Magnetic measurements were performed at 50 and 400 Hz after different thermal cycles, corresponding to different gradients of Si and Al.

The power losses are reduced more than 50% in the final material (after dipping and annealing) compared with the original. It appears that the annealing process gradually reduces the power losses, reaching the lowest value already before a homogeneous concentration profile is obtained over the sample thickness. A smooth concentration gradient is preferable. This can also be shown through modeling of the magnetic behavior with the concentration gradient. The reduction of power losses is more pronounced at 400 Hz, proofing the importance of the skin effect. A further advantage of this procedure is the short annealing time after hot dipping. The tensile stress-strain behavior shows that the ductility of material with Si-Al concentration gradients was improved compared to a homogeneous 6.5 m-% Si.
Aiming at the Ideal Texture for Electrical Steels

F. J. G. Landgraf, (1) T. Yonamine, (1) and I. G. S. Falleiros (2)

(1) Institute of Technological Research (IPT) of the State of Sao Paulo, Brazil
(2) Universidade de Sao Paulo, Brazil

Based on the possible ability of strip casting to produce (100)<0vw> fibre textures by directional solidification, experiments of rolling, annealing and magnetic measurement were performed on samples that were directionally solidified by other means. Samples with a final texture of strong [100]<012> and weak [100]<011> components were obtained in steels with 3%Si and 0.2%Al. $B_{50}$ values of 1.64 T were obtained in ring specimens. Starting samples have columnar grain sizes of about 2mm diameter misoriented about 10°, on the average, relative to a perfect <100>/ND. Cold rolling produced the expected rotated cube [100]<011>. Further processing steps led to the final texture mentioned above. The paper presents the texture evolution along the processing steps and calculates the average magnetocrystalline anisotropy energy for each step.
High Frequency and Nonsinusoidal Losses in Magnetic Steels

P. Pillay and L. Mthombeni

Clarkson University, Potsdam, New York, USA

This paper will present some of the work being done in the determination and categorizing of nonsinusoidal and high frequency losses in lamination steels at Clarkson University. This is done in collaboration with a consortium consisting of Black & Decker, Ispat Inland, Magsoft, Eaton Corporation, Globe Motors, Lamination Speciality Corporation and KJS & Associates. Correlations between toroid and Epstein square testing have been done, and the possibility of predicting nonsinusoidal losses from sinewave data examined. The impact of PWM on losses has also been determined. Current work on examining a variety of different lamination materials will also be described.
A New Generation of High Permeability Fully Processed Electrical Steels

S. Jacobs\textsuperscript{(1)}, M. De Wulf\textsuperscript{(2)}, E. Leunis\textsuperscript{(2)}, E. Cogoluegnes\textsuperscript{(3)} and B. Fenaille\textsuperscript{(3)}

\textsuperscript{(1)} ARCELOR FCS Commercial
\textsuperscript{(2)} Arcelor Research Center OCAS, Zelzate, Belgium
\textsuperscript{(3)} St.-Chély d’Apcher, Production Site Electrical Steels, ARCELOR FCS

Fully processed electrical steels are widely used as core material for e.g. motors, generators, small transformers and ballasts. Amongst others, more stringent environmental laws motivate our customers to develop higher efficiency versions of their machines. The increase of permeability of the steel laminations leads to an improved magnetising behaviour and is known for improving the applications’ performance and efficiency. We therefore developed a high permeability product range, which complies with very distinct market demands. Indeed, the application of low-alloyed grades, which intrinsically have a good permeability, is different from those with a high Si-content, which essentially have low losses. For instance power-generating machines need very low losses; traction and industrial motors a medium loss level; whereas small transformers and ballasts use medium and higher loss grades. The electro-magnetic ballast producers typically use grades with 4 to 5.3 W/kg at 50Hz/1.5T/0.5mm, but need increased polarisation levels, in order to compete with the electronic ballast industry. For power generation, the challenge is to keep losses as low as e.g. 2.5 W/kg at 50Hz/1.5T/0.5mm, hence by using a substantial amount of Si and at the same time finding a way to compensate for the detrimental effect of Si on the saturation induction.

The first generation of high permeability electrical steels of our company was based on an approach targeting for a minimisation of the presence of inclusions and precipitates, as these are known to be harmful to the magnetic domain wall mobility. This approach successfully led to a range of high permeability products. As it is clear that this method, making use of cleaner chemistries, requires more expensive liquid steel elaboration processes, it is not the most cost-effective way ahead. As a consequence, alternative processing routes were explored and led to a new generation of high permeability grades.

The processing of the new generation of electrical steels we now propose, is based on a controlled inclusion and precipitate formation mechanism. The key issue however, is the modified chemistry and the enhanced thermo-mechanical process, which have been developed for texture and grain size optimisation. The presentation discusses in more detail the microstructure and texture optimisation, which has been realised in this product range and its impact on the obtained magnetic performance.
The Development of Non-Oriented Electrical Steel in Baosteel

B. Wang (1) and Y. Huang (2)

Baoshan Iron and Steel Co, Ltd., Shanghai, China
(1) Electrical Steel Department, R & D Center
(2) Electrical Steel Section, Marketing Department

Since the first coil of cold rolled non-oriented electrical steel was made in 2000, Baosteel has established mass production techniques, facilities and systems for NGO steel production. Served to customers with good quality, Baosteel is focusing on products with not only excellent magnetic properties, but also high accurate tolerance in dimension and good punchability and weldability. Recently, a series of new products such as B50AY-2, B50A1300M and B50A1300H with low core loss and high induction have been developed for various customer applications. These new products have satisfied requirements from customers mostly the in Air-con compressor, Motor lamination and EI lamination industries.

Keywords:
Low core loss, High induction, Punchability, Weldablity, Compressor, Motor, EI lamination
The power losses of a 3% (by weight) non-oriented Si-steel containing 0.4% Al (by weight) have been measured. The steel was rolled to thicknesses between 0.05 and 2.00 mm. After annealing, each gauge nominally had the same microstructure. Using an Epstein frame, the losses were measured under sinusoidal polarisation of up to 1.8 T and at frequencies between 25 Hz and 10 kHz. The results are discussed in terms of different loss contributions using simple models. The optimum thickness for different frequencies is discussed, in view of its relevance to high frequency applications, such as hybrid drives and microturbines.
On the Use of Integrated Average Core Loss and Permeability for Electric Motor Performance Prediction

R. Heideman, C. Riviello, S. Dellinger, D. Ionel, K. Blazek, and O. Lanzi

(1) AO Smith Corp., Milwaukee, Wisconsin, USA
(2) Ispat Inland Inc., East Chicago, Indiana, USA

Previously published work by Blazek and Riviello [1], proposed that integrated average core loss (IACL) and integrated average permeability (IAP) of cold rolled motor lamination (CRML) steel could be used to predict motor performance. The IACL and IAP are global parameters, calculated based on the non-linear curves of magnetic properties on a 0 to 2T flux density range, and therefore were thought to provide a better measure of steel “goodness” than the standard 1.5T values used for CRML steel specification.

Fundamental concepts, such as the “goodness” of an electric motor [2], the scaling laws of electrical machines [3], the statistical relationship between the rating of a motor and its parameters [4], have continuously attracted the attention of scientific researchers and engineers. In the light of such previous work, an attempt at investigating the possibility of a direct relationship between IACL and IAP on one hand, and motor performance, on the other hand, has been considered a worthwhile effort.

To test the IACL and IAP hypothesis, induction motors were fabricated using six steels alloys and tested. Epstein testing was done on the six steel alloys to determine their IACL, IAP, and a limited range IAP. In addition to these properties, the standard 1.5T core loss and permeability values were also documented. A statistical analysis of these properties was completed to determine which steels were statistically different. A similar analysis was performed on motor test data to determine which steels produced statistically different motors. A third, final analysis, based on the information from the first two, was performed to determine multivariable linear regression models in between steel global parameters and motor performance, which included efficiency, current, and power factor. Full details of the mathematical procedures will be presented in the paper.

According to the non-linear electromagnetic theory of induction motors, the motor performance is affected by a combination of steel permeability and core loss. The merits of the IACL and IAP concepts in providing – based solely on material and motor test results – an indication of the relative proportions in which the permeability and core loss, respectively, affect the performance of a particular motor design have been illustrated. None of the regression models developed were able to fully overcome the inherent challenges posed by the non-linearity of the motor physical system and the use of the averaged material properties. The accuracy of the regression models did not provide the confidence level required for direct use in steel substitution decisions. Furthermore, the values of the regression coefficients are dependent of motor design, i.e. the magnetic circuit operating point, and therefore direct generalization over a wide range of motor ratings and sizes is not strictly applicable. In conclusion, the IACL and IAP model could be useful in predicting trends, but its use for exact motor performance prediction is limited.

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Magnetics for Security

R. Indek
Center for Security Technology, Washington University, St. Louis, Missouri, USA
The Application of Magnetorheologic Fluids for the Safety of our Civil Infrastructure

S. Dyke
Department of Civil Engineering, Washington University, St. Louis, Missouri, USA
Magnetostructural Transitions for Magnetic Cooling

M. Pasquale
IEN Galileo Ferraris, Torino, Italy
New Excitation Methods for Direct Drive DC Brushless Motors with Complex Electromagnetic Core Designs

Z. Soghomonian, Z. Rahman, and K. Martin
WaveCrest Laboratories, Dulles Virginia, USA

In direct drive DC brushless motor applications, the main incentive is to increase the torque and power density of the machine design by improving the architectural configuration of the stator and rotor constituents. This normally requires careful consideration in the design of the magnetic circuit topologies, which promotes significant weight reduction in the magnetic mass as well as improvement in the form factor of the magnetic design. Such weight reduction is of paramount importance in minimizing the inertia and unsprung mass in in-wheel hub motors.

Significant performance improvements in motor characteristics are seldom achieved completely with the use of conventional, laminated electrical steels. This is because there are classical limitations as to how much the form factor can be improved to optimize the winding factor and to reduce the bulk of the magnetic mass required for generating the desired torque and power output with the intended cooling.

In most designs, the limitations in 3d isotropic properties of the lamination steels are compounded by the limited freedom in 3d shaping of the lamination stacks. It is therefore difficult to truly optimize the critical path of the magnetic constituents in the motor architectures. Furthermore, there are the classical issues concerning interlaminar eddy, hysteresis and excess eddy current losses, which stem from normal and planar flux distributions in complex magnetic structures of the motors.

A new range of permanent magnet DC brushless motors have been developed for in-wheel and near-wheel propulsion applications, which have the potential of improving the torque-to-weight ratio to 20 Nm/kg. The most important factors in inverted (direct drive) DC brushless motors are manufacturing cost, motor package size, adequate thermal management, lower unsprung masses and active weight, stator form factor as well as, simplification and modularization of the design for cost-effective manufacturing, servicing and reproducibility.

These objectives are met, in part, by careful weight reduction in the active mass of the motor with the use of Soft Magnetic Composite (SMC) materials and different excitation configurations. In these new designs the machines have segmented magnetic stator design [1, 2] that eliminates the mutual induction among different phases, thus allowing flexibility in field weakening controls.

Due to the changes introduced in the design of the magnetic circuit of the motors, unique electromagnetic cores are developed that improve the form factor, minimize the active mass and core losses of the motor whilst maintaining the desired motor performance characteristics at the operating frequencies and induction. Different excitation configurations are discussed which complement the improvement made in form factor of the magnetic constituents. This paper discusses the on-going work at WaveCrest on its segmented magnetic motor topology, which is further complimented with proprietary inverter power electronics and control algorithms. Some results are presented in this paper, which are supported with typical torque and speed plots. The control algorithm used is a subject of a different paper presented at this symposium under the title “Prephase d-q Model for Multiphase PM Motor with Segmented Magnetic Paths”.
Seven Phase Brushless Synchronous Motor Reduces Inverter Size

R. Dhawan and Z. Soghomonian
WaveCrest Laboratories, Dulles, Virginia, USA

This paper illustrates a unique inverted DC brushless motor configuration intended for propulsion and transportation systems, and discusses the design factors influencing the inverter architecture. The paper discusses the magnetic design along with the motor characteristics, which are utilized further for the design of the electronics. The first three sections discuss the motor magnetic design. Section four discusses the inverter design. The paper concludes with possible improvement options for the inverter.
Magnetic Losses in Brush-Less DC Motors

B. Fahimi
University of Missouri-Rolla, Rolla, Missouri, USA