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ALLOYS FOR MAGNETIC AND ELECTRICAL COMPONENTS OF AUTOMOTIVE ELECTRIC MACHINES

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SUMMARY

Nowadays, there are different kind of electrical machines which used in the vehicles for different purposes. The state of art of electric machines, associated components and contemporary trends of their development improved according to the demands expecting from electric machines. Recently new topologies of high torque density motors, high speed motors, integrated motor drives and special motors have been developed. Progress in electrical motors is stimulated amongst others by new materials, new areas of applications, impact of power electronics, need for energy saving and new technology challenges. In the market, the development of electric machines also are developing by computer software.

In the last years, the car makers are used different kind of machine. In this thesis, the most common ones which are Lundell Alternator(Machine), Induction Machine(IM), Permanent Magnet Synchronous Machine(PMSM), Axial Flux Permanent Magnet Synchronous Machine(AFPMSM), Switched Reluctance Machine(SRM) and Synchronous Reluctance Machine(SYR) are discussed by explaining their properties and duties in the vehicle.

The one of the most critical factor together with the design of the machine is also to use proper material in the electrical machines. By considering the material properties , different kind of electrical steels are used to obtain targeted performances. In addition, rising energy costs have created the need for low loss, high permeability, low residual and high efficiency electrical steels to produce energy efficient devices. In the light of new technologies, the permanent magnets are used in the electrical machines. In this thesis, the most common electrical steels and alloys which are Pure Iron(Fe), Iron-Silicon(Fe-Si), Neodymium-Iron-Boron(Nd-Fe-Br) and Iron-Cobalt-Vanadium(Fe-Co-V) are defined as most effective one in the market by explaining their magnetic properties, compositions, phases and processes

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1. COMMON ELECTRIC MACHINES USED IN THE VEHICLES

1.1. LUNDELL ALTERNATOR/ACTIVE RECTIFIER

The Lundell alternator is the predominant machine used as a generator in conventional vehicles due to its robustness, reliability, wide speed range and low cost. The main parts of the Lundell Alternator are Rotor, stator and windings which wound about the rotor. The common version of this electric machine in the industry is a three-phase sixteen-pole delta-connected alternator. [1] The Lundell alternator is the traditional automotive alternator due to its possibility for constant terminal voltage under a range of operating speed. This is achieved by weakening the excitation field at higher operating speed. The rotor has a dc coil, which magnetizes claw fingers on two pole pieces. These excite a 3-phase winding, which is star or delta connected to a rectifier. Reducing the dc coil current reduces the excitation field strength and allows modulation of the terminal voltage over the varying speed range.

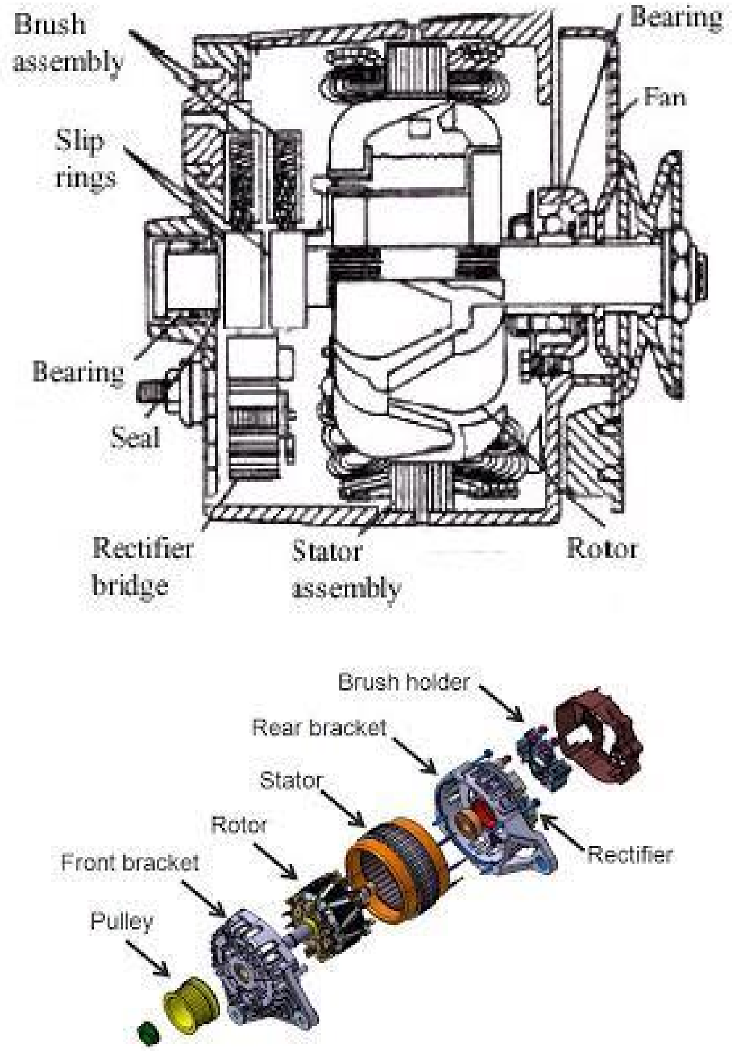


Figure 1 Lundell Alternator Structure [2] [3]

The efficiency and power output are limited in the Lundell alternators, and this is the major drawbacks of Lundell machine due to the high electric power requirements in new electric cars. The conventional Lundell machine has a claw pole rotor with a single excitation coil wound axially which surrounded by two solid iron pole pieces. The stator is composed of a slotted laminated iron core and a three-phase overlapped winding. Generally, the rotor poles number is fixed at 12 poles whereas the pole number is fixed at 36 poles at stator. In this case. number of poles is considered as very important design parameter and if it is increase, the magnetic losses will increase due to higher electrical frequency.

Generally, Lundell alternators are characterized by low efficiency due to important mechanical, copper and magnetic losses. Main losses generally due to stator copper. Powerful magnetic excitation of the rotor, combined with specific geometry involves significant magnetic leakage and it is important when the magnetic material is saturated. For a better exploit of the magnetic excitation, permanent magnets are using to polarize magnetically the rotor in the opposite direction. In conclusion, the magnetic saturation is low in the rotor which allows for a larger useful flux. The wire is preferably made of nonmagnetic material. [4] [5]

The excitation current and the excitation magnetic flux of the machine are DC in the rotor construction and there is no need to build the rotor core with laminated. The magnetic flux on the material is not alternative and due to this reason. the rotor is made from a cast iron. The magnetic flux created by the excitation circuit and each of iron claws become a pole. The stator of the machine built of laminated sheets to reduce the hysteresis and Foucault losses as small as possible. The laminated sheets contain the cutting for the slots. In the Lundell Machine, to create a magnetic field to supply current, ferromagnetic materials are using but to reduce the losses, the soft ferromagnetic materials are preferred instead of hard ferromagnetic materials. [6]

The rotor core structure may further comprise spacers disposed in the clearances in association with the permanent magnets, respectively, and each having low magnetic flux permeability.

There are two main components of an electromagnet: the ferromagnetic core and magnet wire windings. The choice of core material impacts the overall efficiency and power output of the alternator. The material properties that will be considered when deciding on the core material are permeability, saturation, coercivity, remanence, and resistivity. High permeability is desired feature because a core that would reach peak magnetic flux more quickly would allow for an increase in the generation of electrical power. High saturation is required because the core must maintain the greatest magnetic flux possible. Low coercivity is desired because the magnetic flux must return to its lowest levels with the least amount of an applied magnetic field. Low remanence is desired because the design wants a core that would have as little remaining magnetic field when the rotor was deactivated so that there would be no stray effects. Low resistivity is desired because a core that resisted an imposed electric field as little as possible. High purity iron matches these properties and therefore will be considered as the core material for the rotor.

Regarding the individual components of the alternator, the choice of magnet wire influences power output. Magnet wire is the thin, insulated copper wire coiled around the iron core in the rotor.

The stator consists of an iron core that surrounds the rotor. The iron core completes the magnetic circuit between the rotor and stator. The stator then has iron teeth that extend from the core and point towards the rotor poles. As these teeth are made of iron, the teeth provide another path to complete the magnetic circuit. In the gaps between the stator teeth lie coils of copper wire. The alternating magnetic flux, generated from the rotor, induces a voltage in the coils. From this process, alternators can generate electrical energy from mechanical energy. [7] [8]

1.2. INDUCTION MACHINE

Three-phase induction motors are also called asynchronous motors. There are some different arrangements:

- Induction machine with stator and rotor: Main parts stator, rotor and stator windings.
- Distributed winding inside stator: three phase one pole-pair stator with distributed winding pattern
- Rotor and induction motor with sliprings
- Squirrel-cage rotor for IM
- Cross section of squirrel cage rotor with drop shaped bars

In general, there are two types of rotors for IM: The squirrel-cage and the slip-ring rotor cage. Efficiency is lower than PMSM machines. [9]

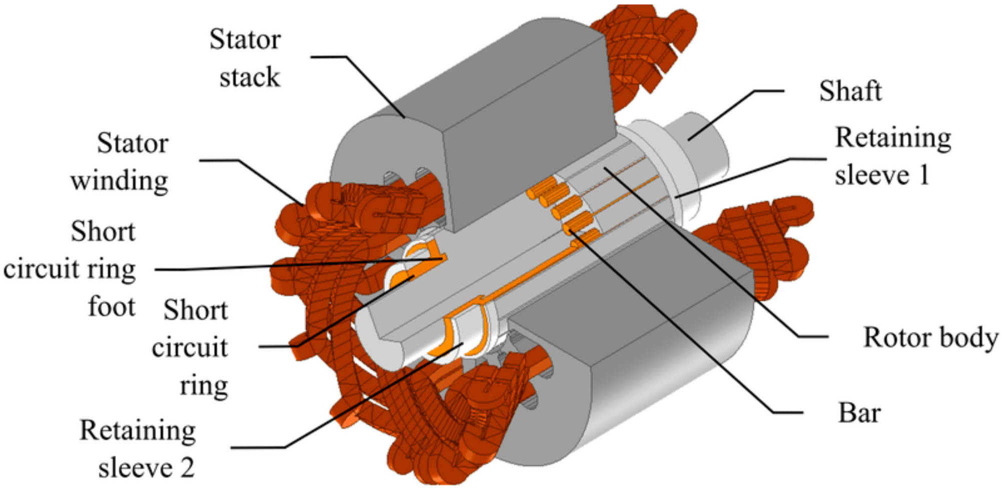


Figure 2 Induction Machine Structure [10]

Traditionally, IM has robustness and mature manufacturing technology and control method. Generally, it is cheaper than Permanent Magnet machines.

It has lower power density. Constant power region is not as wide as PM. The squirrel cage material of the rotor is copper or aluminium.

The material should have high conductivity such as copper. The cages generally produced from aluminium or copper and the rotors can be manufactured by either casting or a fabrication approach, where the squirrel cage is brazed together from many machined pieces. The lowest cost approach for producing rotors is by die casting aluminium in the squirrel cage, but as the electrical conductivity of pure copper is more than 60% greater than that of aluminium, die-cast copper rotor generally gives significant efficiency improvements. An alternative to the die-casting avenue is the fabricated cage (with copper bars).

Excitation comes from stator; efficiency is low and it needs small air gaps. The stator frame consists of laminations of silicon steel and its coils are normally made of copper; round conductors of many turns per coil are used for small motors, and rectangular bars of fewer turns are employed for larger machines. The coils are electrically insulated.

The magnetic part of the rotor is also made of steel laminations. In such machines there is no need to insulate the conductors from the iron. The squirrel cage often consists of an aluminium casting incorporating the conductors, the end rings, and a cooling fan. For larger motors, the squirrel cage is made of copper, aluminium, or brass bars welded or brazed to end rings of a similar material.

In general, commonly, for stator and rotor cores, non-grain oriented electrical steel is chosen as a core material due to its isotropic magnetic properties that shall reduce the core loss in rotating machine application. [11] [12] [13] [14] [15]

1.3.PERMANENT MAGNET SYNCHRONOUS MACHINE

A permanent-magnet synchronous motor (PMSM) uses permanent magnets embedded in the steel rotor to create a constant magnetic field. The stator carries windings produce a rotating magnetic field by connecting to AC supply. At synchronous speed the rotor poles lock to the rotating magnetic field. Permanent magnet synchronous motors are like brushless DC motors. [16].

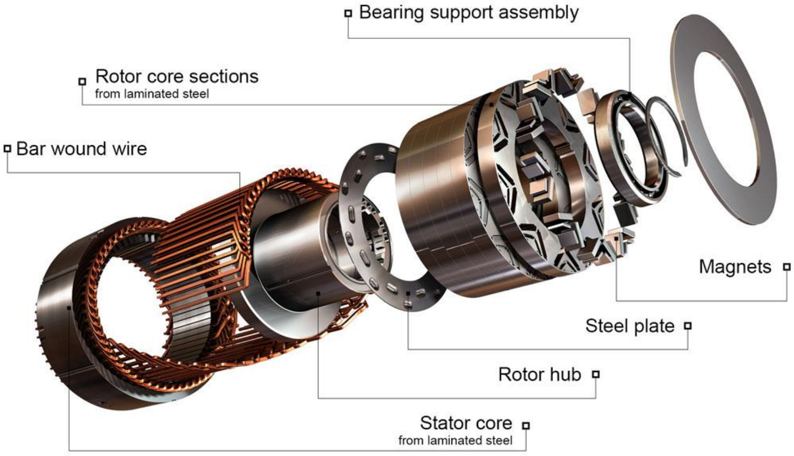


Figure 3 PMSM Structure [17]

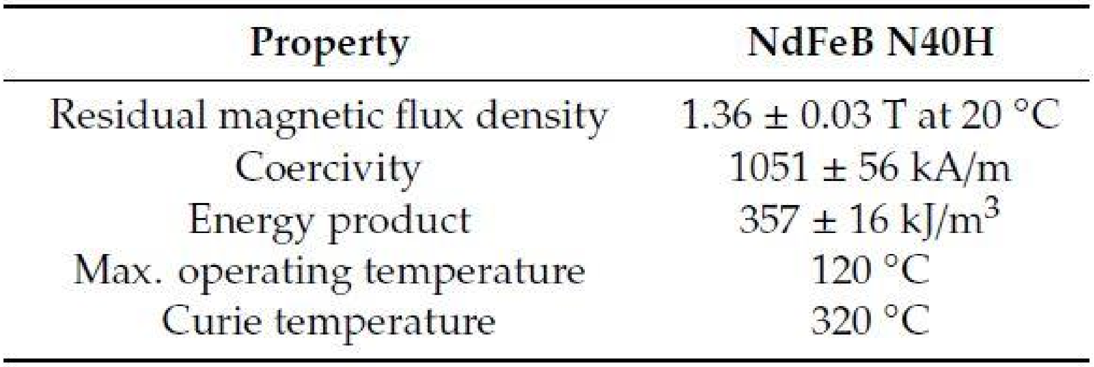
T field excitation winding is mounted to the rotor of the synchronous machine. The rotor is excited by a DC power supply via permanent magnets.

The downsides are increased cost because of the permanent magnets (PM) and the risk of demagnetization from cracks caused by vibrations or high temperatures during motor operation, causing a loss of power.

The magnetic core of the PMSM (interior) for both rotor and stator are soft magnetic material. Desirable properties high permeability and saturation point low losses and for the rotor, sufficient mechanical strength to support required rotational speed. Used material generally is FeSi (Silicon-iron) alloy. Also, FeCoV alloy (vanadium-cobalt-iron) is another alternative. But at high frequency, FeCoV leads to increase magnetic losses. The rotor shaft must be made from a non-ferromagnetic material. Low electric conductivity, low magnetic permeability and high tensile strength are desired. Used material is dependent also size but ASI 316 stainless steel could be example.

The permanent magnets provide the field excitation. Permanent magnets specifications are high energy density, magnetic coercivity, remnant magnetic flux density and working temperature. Between the permanent magnets, Neodymium-iron-boron NdFeB is the most preferred material in electrical machine design due to its higher values of energy density and remnant magnetic flux density than other alternatives.

Table 1 NdFeB properties



Property	NdFeB N40H
Residual magnetic flux density	1.36 ± 0.03 T at 20 °C
Coercivity	1051 ± 56 kA/m
Energy product	357 ± 16 kJ/m^3
Max. operating temperature	120 °C
Curie temperature	320 °C

The electromagnetic or magnetic circuits stators and rotors in rotating electrical machines are made of ferromagnetic materials. In these circuits the electrical energy is transformed into to mechanical energy. To minimize the size of the electromagnetic circuit, a magnetic circuit used magnetically soft steel. To minimize the size of the electromagnetic circuit it is required to use the soft magnetic steel for stator and rotor cores. [18] [19]

1.4. AXIAL FLUX PERMANENT MAGNET SYNCHRONOUS MACHINE - AFPMSM

AFPMSM is widely used in the automotive electric industry due to its high power and torque density, minimize torque ripple and due to the design consideration its pancake structure. The PM material has a high surface area to thickness which makes it more vulnerable to permanent demagnetization at high temperature.

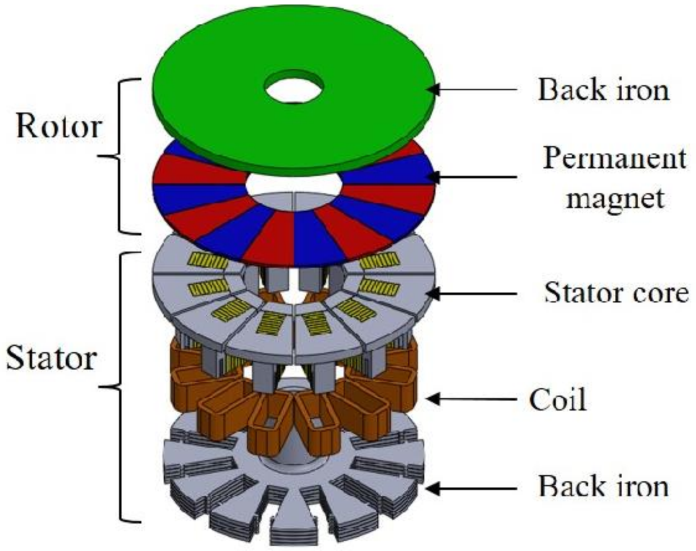


Figure 4 AFPMSM Structure [20]

It is commonly used in electric vehicle powertrains and in-wheel motors. The magnetic core material is commonly NdFeB. As it in the PMSM, the main parts are the rotor, stator, and windings. The type of mounting can be different according to using areas. [21]

The different pancake-type profile of the rotor and stator of axial flux motors makes it possible to generate various and easily changeable designs. Axial permanent magnet motors advantages and disadvantages according to conventional motors can be summarized:

Advantages:

- Wider radius/length ratio
- Planar and adjustable air gap
- Higher power density
- Ideal design availability because of smaller volume and lower weight.
- Availability for higher frequency or lower speeds

Disadvantages:

- strong axial magnetic attraction force between the stator and rotor.
- fabrication difficulties
- difficulties in mounting the machine and keeping the stationary air gap
- manufacturing time is longer
- High costs in manufacturing because of longer time

In the stator, the windings are placed of stator inside and creates the main power. Stator core steel can be attaching piece by piece and it must be solid for axial flux motors. Because there is no symmetrical structure at axial dimension. Stator steel core plate becomes from a one piece of roll strip steel. Stator steels need to be wrapped tightly not to leave any gap. Desired dimensions for stator core are prepared from wrapping tightly one-piece roll strip steel. Also, the stator core is welded in 90 degrees to keep it tight. Welding stator steel must be carefully havoc magnetic circuit.

There is one rotor in single air gapped axial flux motors. There are permanent magnets at the stator side of rotor. These magnet’s B-H characteristic influences directly to the motor’s output power. [22]

1.5. SWITCHED RELUCTANCE MACHINE - SRM

The SRM is a cost-efficient motor without need of expensive rare-earth materials. In general, the SRM have some component: exciting windings, no-exciting windings, shaft, rotor and stator. Both the stator and rotor have salient poles. There is no permanent magnet or other external excitation in a SRM. The generation of the reluctance torque is independent on the direction of the flux. The torque generation of SRMs is based on reluctance force unlike other types of motors. Just some coils are excited at a point in time and the rotor will be pulled towards this coil which causes a rotation of the rotor. Its robust structure allows the SRM to run at very high speeds and high temperature and it can also be used as a stepper motor. But according to IM and PMSPM, it has low efficiency, high torque ripple, noise, and vibration.

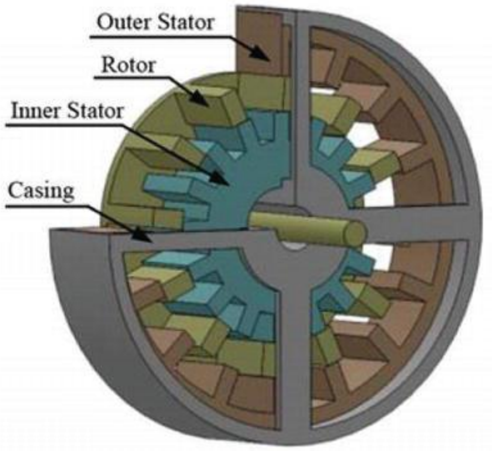


Figure 5 SRM Structure [23]

It has neither a permanent magnet nor a second winding in the rotor. Only silicon steel and stator winding are needed in an SWR. The copper can be reduced by having concentrated winding which provide short end-windings. To improve the efficiency, better iron core is needed in the SWR to be competitive.

The rotor comprises of stacked iron laminations and stator with copper windings.

Why we should choose SRM:

- High instant power and high-power density.
- High torque at low speeds for starting and climbing, as well as high power at high speed for cruising.
- Very wide speed range.
- Fast torque response.
- High efficiency over wide speed and torque ranges.
- High efficiency for regenerative braking.
- High reliability and robustness.
- Reasonable cost. [9] [12] [24]

1.6.SYNCHRONOUS RELUCTANCE MOTOR – SYR

In principle, this machine is like the traditional salient pole synchronous motor but does not have an excitation winding in the rotor. In this machine only the rotor is constructed by flux-barriers. The main advantage of the SyR relies on the absence of rotor copper losses that permits continuous torque that can be higher than an IM of the same size. The other important features of the SyR are:

- The rotor is potentially less expensive than both PM and IM due to cancelling cage, winding and magnets from its structure
- More simpler control system

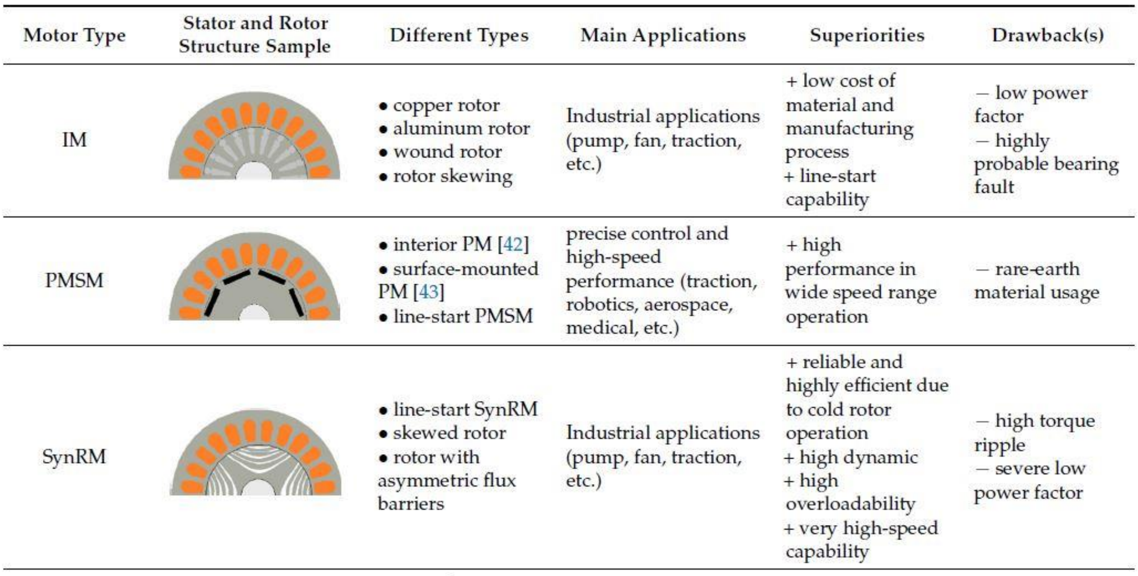
A synchronous reluctance motor for pure electric vehicles is proposed to demonstrate how a low-cost solution without PMs is able to meet the hard requirements typical of an electric car. Generally, they have lower power and density, higher noise and lower power factor. But through an optimized motor design, it is possible to obtain hight torque density and efficiency adopted to automotive applications. By adding a proper amount of cheaper PMs (Ferrite) in the rotor flux barriers of SyR motor similarly to internal permanent magnet motors configurations, performances close to those of PM motors can be obtained at a lower cost. This topology is referred to as permanent magnet assisted synchronous reluctance motor (PMA-SyR), and the available torque is obtained thanks to the contribution of both reluctance torque and synchronous torque. This gives rise a torque improvement of about 20% respect to the SyR without PM. The use of ferrite magnets seems to be a good compromise for using permanent magnets without drastically increasing the motor cost. [12]

The rotor of a synchronous reluctance motor includes only magnetic steel. In stator design, the active materials are used for laminations and stator conductors.

These solutions rely on high reluctance torque, thus theoretically needing no PM material in the rotor structure. They have relatively low material costs, low rotor losses and are considered as robust. On the other hand, lack of the permanent magnetic field in the rotor is penalized with lower torque density, lower power factor, and higher torque ripple.

The rotor needs high magnetic conductivity (high permeability). In rotor, laminate steel only used. [25] [26]

Table 2 Comparison of some machine types



Motor Type	Stator and Rotor Structure Sample	Different Types	Main Applications	Superiorities	Drawback(s)
IM		• copper rotor • aluminum rotor • wound rotor • rotor skewing	Industrial applications (pump, fan, traction, etc.)	+ low cost of material and manufacturing process + line-start capability	− low power factor − highly probable bearing fault
PMSM		• interior PM [42] • surface-mounted PM [43] • line-start PMSM	precise control and high-speed performance (traction, robotics, aerospace, medical, etc.)	+ high performance in wide speed range operation	− rare-earth material usage
SynRM		• line-start SynRM • skewed rotor • rotor with asymmetric flux barriers	Industrial applications (pump, fan, traction, etc.)	+ reliable and highly efficient due to cold rotor operation + high dynamic + high overloadability + very high-speed capability	− high torque ripple − severe low power factor

SyR has praiseworthy loadability, particularly at lower speeds. This motor can be loaded up to 2.5 times higher than the nominal torque. Owing to the lack of bars in the rotor, the iron loss is roughly omitted. The maximum power factor of SyR depends on the saliency ratio. The higher the ratio the SyR has, the higher the power factor the motor can provide.

Conventional SyR rotor designs use silicon steel laminations including bridges and centre posts. While these bridges and posts are necessary for mechanical reasons, they have a significant impact on reducing the electromagnetic performance. This includes reduced saliency and therefore reduced reluctance torque.

The SyR rotor can withstand high temperatures as well as high centrifugal forces due to its robust construction. Magnetic material needs high permeability. [27] [28]

In general, the machines which mentioned above have different characteristics and different materials are used. The table below is explaining all characteristics of them briefly.

Table 3 Summary of Machines

MACHINE	CHARACTERISTICS	PARTS	REQUIREMENTS	MATERIALS	MATERIAL PROPERTIES
Lundell Machine	Robustness Design Reliability Wide Speed Range High Operating Speed Low Manufacturing Cost Limited efficiency and power output	Rotor	Composed of two solid iron pole pieces Not Laminated Two main electromagnet components: ferromagnetic core and magnet wire windings	Cast Iron (most suitable) Soft Magnetic materials	High permeability High saturation Low coercivity Low remanence Low resistivity
		Stator	Laminated sheets Non-rotating part	Iron Soft ferromagnetic materials	High Permeability High saturation

		Wires	Generally, nonmagnetic materials are preferred	Copper Non-magnetic materials	High conductivity Thin and insulated with copper
Induction Machine	Asynchronous motors Robustness and mature manufacturing technology and control method Low power density Stator efficiency is low	Rotor	There is no need to insulate the conductors from iron.	Cast Aluminium For larger motors: copper, aluminium or brass bar welded.	High conductivity (copper is 60% higher than aluminium)
		Stator	Small air gaps Consist of lamination steel	Silicon steel Laminated electrical steel Fe-Si is most useful	High permeability High resistivity Decreased hysteresis loss Low magnetostriction
		Wires	Round conductors with many turns Electrically insulated	Copper	High conductivity
Permanent Magnet Synchronous Machine (PMSM)	High manufacturing and material costs Permanent materials are used High temperatures or vibrations at high speed causing loss of power	Rotor	Excited by permanent magnets Soft magnetic materials are used for magnetic core	Fe-Si (Silicon-Iron) Alloy Fe-Co-V (Vanadium-Cobalt-Iron) Alloy Nd-Fe-B (Neodymium-Iron-Boron)	High permeability High saturation points Sufficient mechanical strength
		Rotor Shaft	Must be produced from non-ferromagnetic materials	Generally, ASI 316 Stainless steel	Low electric conductivity Low magnetic permeability High Tensile strength
		Stator	Soft magnetic materials are used for magnetic core	Same with rotor	High permeability High saturation points
Axial Flux Permanent Magnet (AFPM)	High power output and torque density Able to minimize torque ripples Planar and adjustable air gaps Availability for higher frequency and lower speeds Cost is high	Rotor	Various and changeable design ability due to pancake structure	Nd-Fe-B	Extremely high performance Poor thermal Corrosion sensitivity is low High conductivity High permeability Mechanical core steel hard and brittle
		Stator	Various and changeable design ability due to pancake structure Stator steel can be attached piece by piece and it has to be solid.	Steel	Steel needs to be wrapped tightly to make small air gaps Stator core should be welded a
		Wires	Electrical insulation	Copper	High conductivity
Switched Reluctance Machine (SRM)	It is cost-efficient motor and no need of expensive rare-earth materials.	Rotor	Iron core	Silicon steels	High permeability High resistivity Decreased hysteresis loss

	There is no permanent magnet or other external excitation SRM can run at high speeds and high temperatures It can be used as stepper motor High instant power and torque density				Low magnetostriction
		Stator	Only silicon steel and stator winding are needed in SRM	Silicon steels	High permeability High resistivity Decreased hysteresis loss Low magnetostriction
		Wires	Electrical insulated	Copper	High conductivity
Synchronous Reluctance Machine (SYR)	It has not an excitation winding in the rotor. Low-cost solution without Permanent magnet material Lower power, torque and density Higher noise and lower factor Also, PM material can implement to increase torque and power Ferrite magnets are most proper ones High reluctance torque Availability to loadability at low speeds. High dynamic and reliable design	Rotor	Only rotor is constructed by flux barriers There is no rotor cage, winding and magnets in its structure Include only magnetic steel Low rotor losses and robust Withstand to high temperature	Iron Silicon steel	High magnetic conductivity High permeability Can be laminated
		Stator	Active materials are used Laminated	Four steel grades M600-100A, M400-50A, M330P-50A, and NO20	High permeability High resistivity
		Wires	Electrical insulated	Copper	High conductivity

2. MATERIAL DEFINITIONS AND THEIR CHARACTERISTICS

2.1. SOFT MAGNETIC MATERIALS GENERAL INFORMATION

2.1.1. Overview of Electrical Steel

The addition of silicon in iron greatly improves the physical properties of electrical steels. Electrical steels have the following desirable properties:

- High permeability - increased capacity to support magnetic fields
- Low magnetostriction - low tendency to expand or contract in magnetic fields
- High electrical resistivity - lessens the core loss by reducing the eddy current component
- Decreased hysteresis loss - low hysteresis loss means less wasted energy in the form of heat from alternating magnetising force

2.1.1.1. Non-oriented fully processed electrical steel

Non-oriented, fully processed electrical steel has varying silicon levels that range from 0.5% to 3.25% Si. It has uniform magnetic properties in all directions. They do not need recrystallisation processes to develop its properties. The low silicon alloy grades provide better magnetic permeability and thermal conductivity. For high alloy grades, better performance is expected in high frequencies, with very low losses.

2.1.1.2. Non-oriented semi-processed electrical steel

Non-oriented semi-processed electrical steels are largely non-silicon alloyed steel and are annealed at low temperatures after the final cold rolling. The end-user, however, has to provide the final stress-relief anneal according to the steel's intended application. The punch ability of this electrical steel type is better than the non-oriented fully processed type, so organic coatings are not required. Non-oriented semi-processed grades are good core materials for small rotors, stators, and small power transformers.

2.1.1.3. Grain-oriented electrical steel

Grain-oriented electrical steels are composed of iron with 3% Si content with grains oriented to deliver high permeability and low energy loss. Grain-oriented grades have strong crystallographic properties. This type undergoes a recrystallisation process resulting in an enhanced grain structure that exhibits better magnetic properties in the rolling direction of the sheet. Grain-oriented steels are mostly used for non-rotating applications, such as transformers. [29]

2.1.2. Properties and Classifications

Ferromagnetic or ferrimagnetic materials are magnetic materials. Magnetic materials are divided into two: soft magnetic materials and hard magnetic materials. Coercivity is the main criterion and is the IEC Standard 404-1. It recommends 1000 A/m forcing as a value to distinguish both groups. This border is highly symbolic because both classes are completely different. Soft magnetic materials have very low coercivity, while hard magnetic materials have high coercivity. There is also a subclass of rigid magnetic materials called semi-rigid magnetic materials. The figure below presents magnetic materials from one of the main manufacturers, Vacuumschemlze, considering the current challenges.

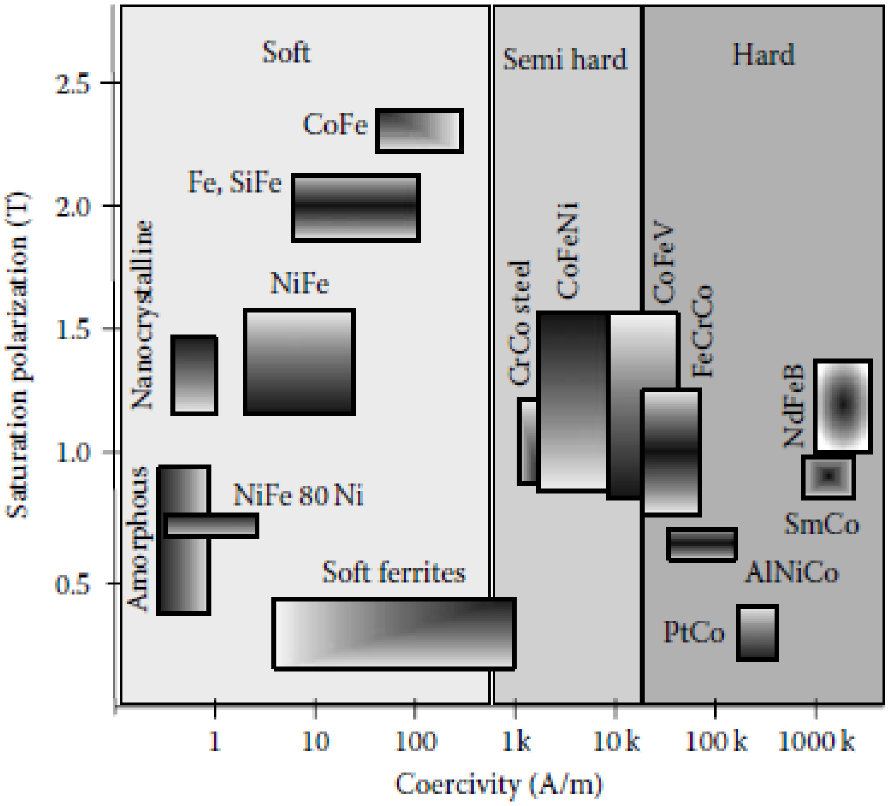


Figure 6 Ranges of commercially available magnetic materials (as an example of products offered by Vacuumschemlze). [30]

Soft magnetic materials have a large scope, and we can divide these products by considering their magnetic performance, applications, cost, and other properties. For example, grain-oriented silicon steel is much harder than non-mechanically oriented steel, so the same punching die will wear after producing fewer elements.

Therefore, the selection of suitable quality and species is quite difficult. For example, top quality steel after product preparation can degrade much more than cheaper material, which can perform better after the same technology. The figure below presents a comparison of the main parameters of typical soft magnetic materials, including their cost.

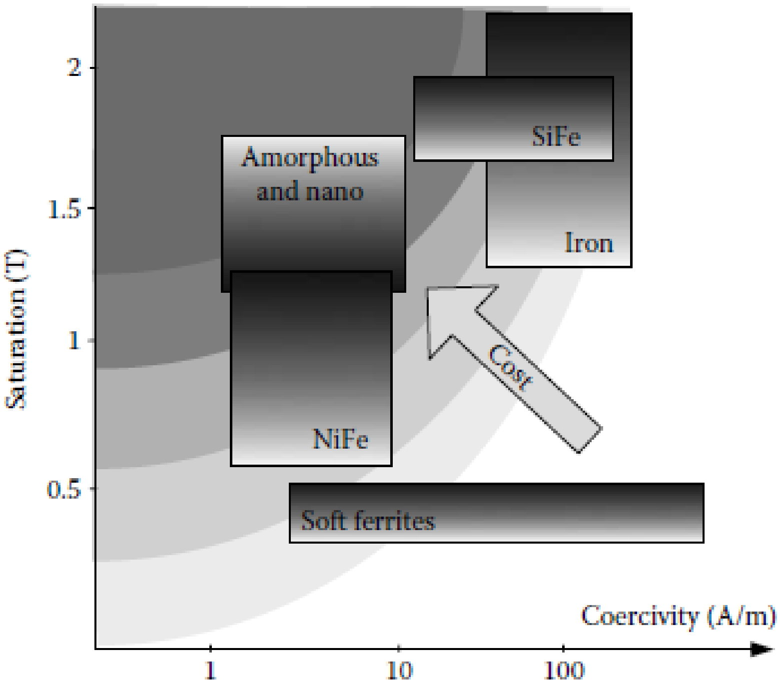


Figure 7 Comparison of the coercivity, saturation, and cost of typical soft magnetic materials [30]

To find best quality in soft magnetic materials would be perfect (high saturation polarization, small losses, small coercivity, small magnetostriction, good mechanical properties, etc.) even at much higher price. But such material simply does not exist. We must accept always some compromises— high permeability at the cost of saturation polarization, small power loss at the cost of saturation polarization, better magnetic parameters at the cost of mechanical properties, etc.

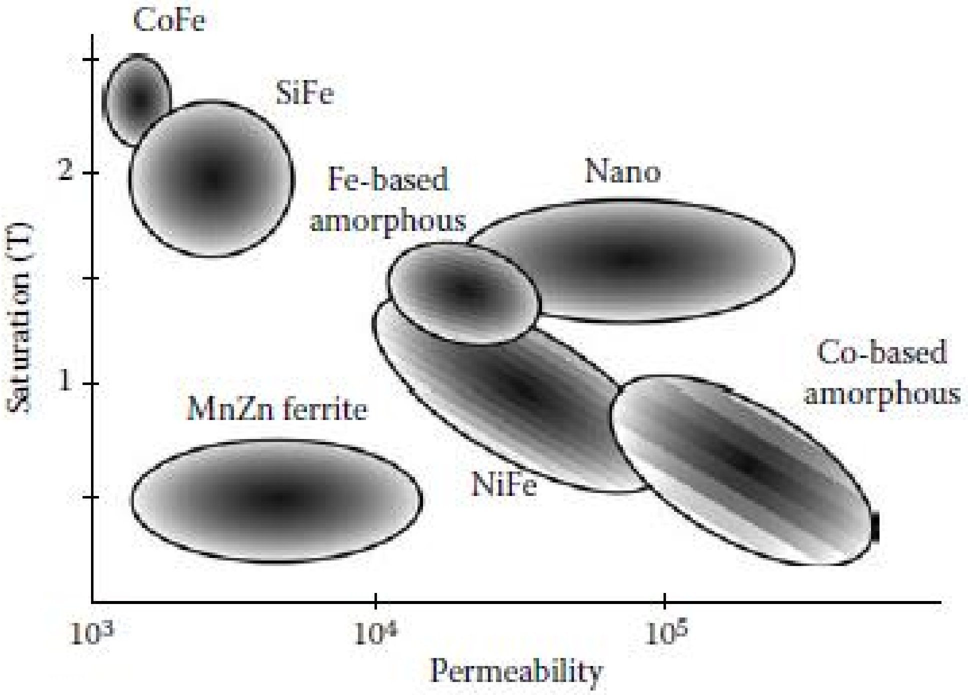


Figure 8 Comparison of the permeability and coercivity of the typical soft magnetic materials. [30]

The main applications of soft magnetic materials are constantly evolving. For example, the main application of silicon steel was in the electrical power industry. But the growing need for electrical power is using higher frequency signals up to MHz. In the high frequency range, electrical steel exhibits extremely high-power loss and must be replaced with nanocrystalline or even ferrite materials.

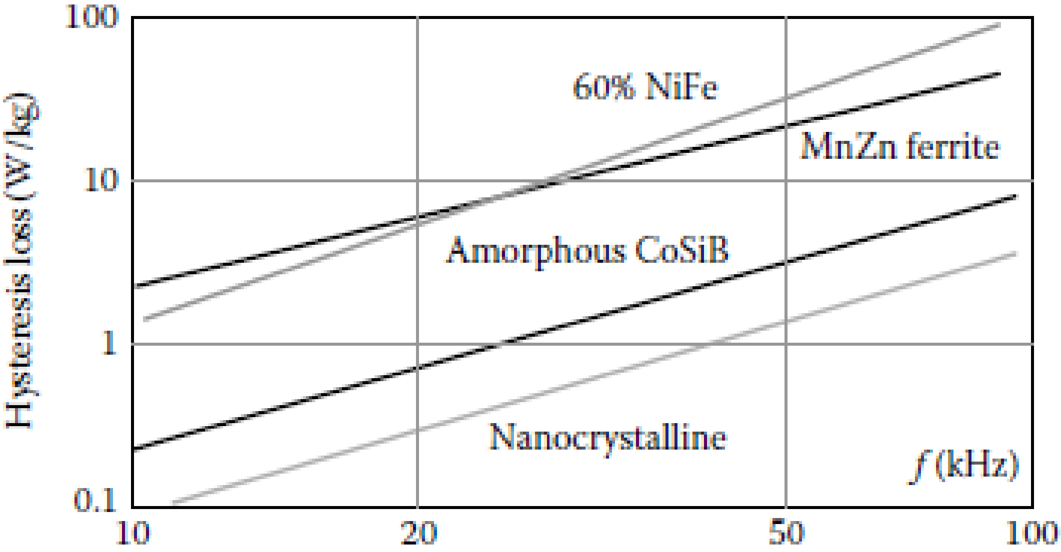


Figure 9 Hysteresis power loss versus frequency of high-frequency materials [30]

If we evaluate various soft magnetic materials, it should be noted that almost 80% of the market is occupied by Fe-Si electrical steel. With ferrites and permalloys (Ni-Fe), this ratio is more than 95%, and we can see that the value of other materials, including amorphous and nanocrystalline, is marginal.

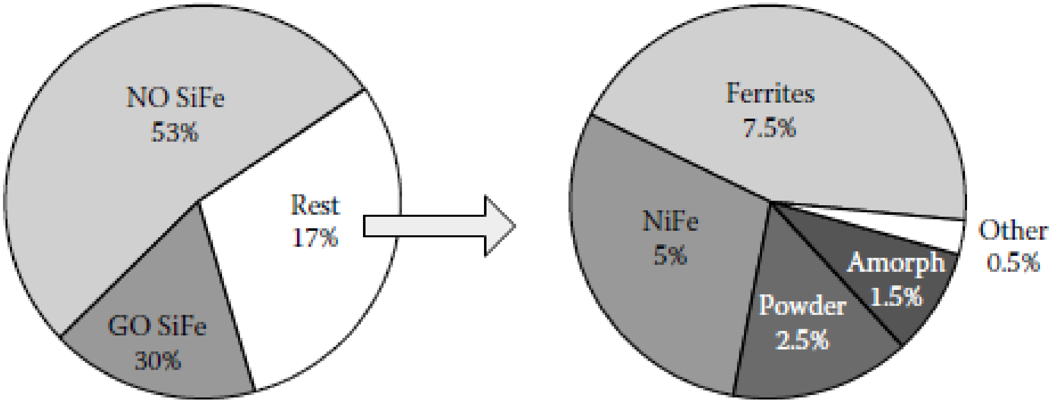


Figure 10 Annual value of world production of soft magnetic materials. [30]

Various features are sought according to the application area. Low power loss and high saturation polarization are the most important factors in electrical power devices. If we only want to choose between silicon steel and amorphous materials (neglecting other factors), we arrive at a contradiction - amorphous materials exhibit smaller power loss but also significantly smaller saturation polarization and vice versa. The table below presents a comparison of parameters for the main soft magnetic materials.

Table 4 Comparison of Parameters for the Main Soft Magnetic Materials

Parameter	**3% SiFe GO**	**FeSiB Metglas**	**Ni80Fe20 Permalloy**	**Co50Fe50 Permendur**	**MnZn Ferrite**
B_s (T)	2.03	1.56	0.82	2.46	0.2–0.5
H_c (A/m)	4–15	0.5–2	0.4–2	160	20–80
P1.5 T/50 Hz (W/kg)	0.83	0.27		1	
P1 T/1 kHz (W/kg)	20	5	10	20	
$\mu_{max} \times 1000$	20–80	100–500	100–1,000	2–6	3–6
Frequency range (kHz)	3	250	20	up to 1 kHz	2,000 NiZn—100,000

For example, if a material is used for magnetic shielding, the permeability will not be important for them, and hence amorphous materials or permalloy is advisable. In the case of high-frequency applications, apart from the losses, permeability with frequency is important, so from Table 4 we can see that, in this case, the materials would be ordered as follows: Fe-Si, Ni-Fe, amorphous/nanocrystalline, Mn-Zn ferrite, Ni-Zn ferrite (and in microwave range, garnets).

Especially important are the Co-Fe alloys because they exhibit high saturation polarization with the highest known value of 2.46 T. The table below presents the typical applications of soft magnetic materials.

Table 5 Typical Applications of the Main Soft Magnetic Materials

Application	Electrical Steel	Fe-Based Amorphous	Powder	CoFe	Ferrite
Power transformers	■	■			■
Distribution transformers	■	■			
Lamp ballasts	■				
Induction motors	■				
Generators	■			■	
Reactors	■	■			
Other motors	■	■	■		
Special transformers	■	■		■	■
Chokes	■		■		■
Power electronics		■		■	■
Instrumentation	■				■
Pulsed power		■			■
Shielding	■	■			

The figure below presents a diversity of soft magnetic materials currently available commercially. The properties of such materials will be discussed in more detail in the following sections.

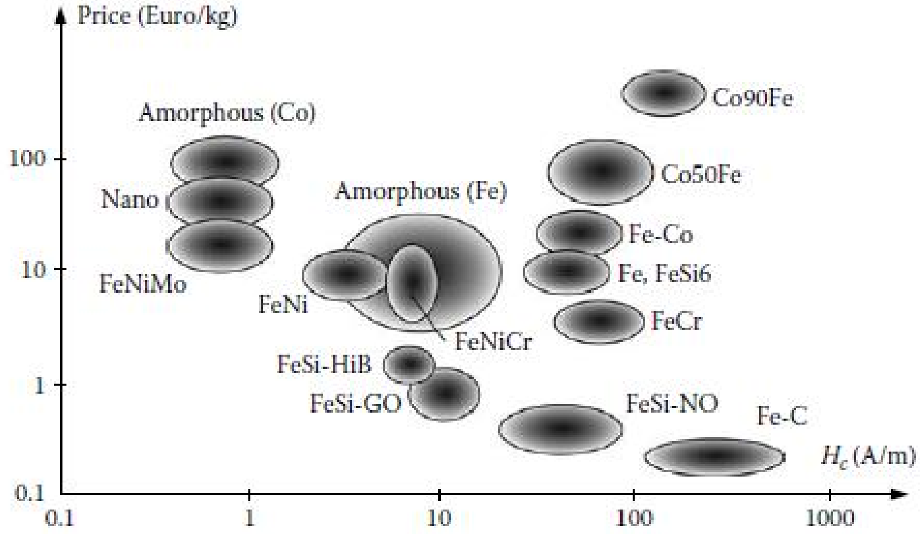


Figure 11 Diversity of soft magnetic materials. [30]

2.2. HARD MAGNETIC MATERIALS

2.2.1. General Remarks

The rare-earth metals such as neodymium and samarium in the production of permanent magnets has significant progress in the quality of permanent magnets. It is illustrated in the figure below.

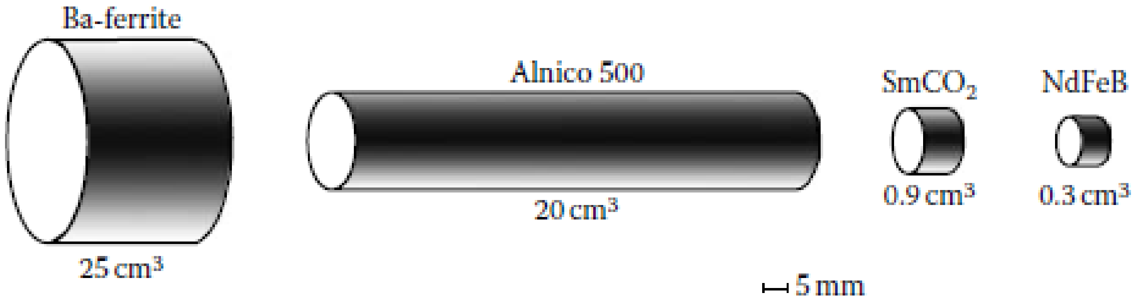


Figure 12 Permanent magnet producing the magnetic field on the flux density 0.1 T at the distance of 5 mm from the face. [30]

Small coercivity is required at soft magnetic materials because hysteresis power loss strongly depends on this value. Conversely, in the case of hard magnetic materials, we need to have as large as possible coercivity and remanence because stored magnetic energy approximately depends on the *Hc·Br* value.

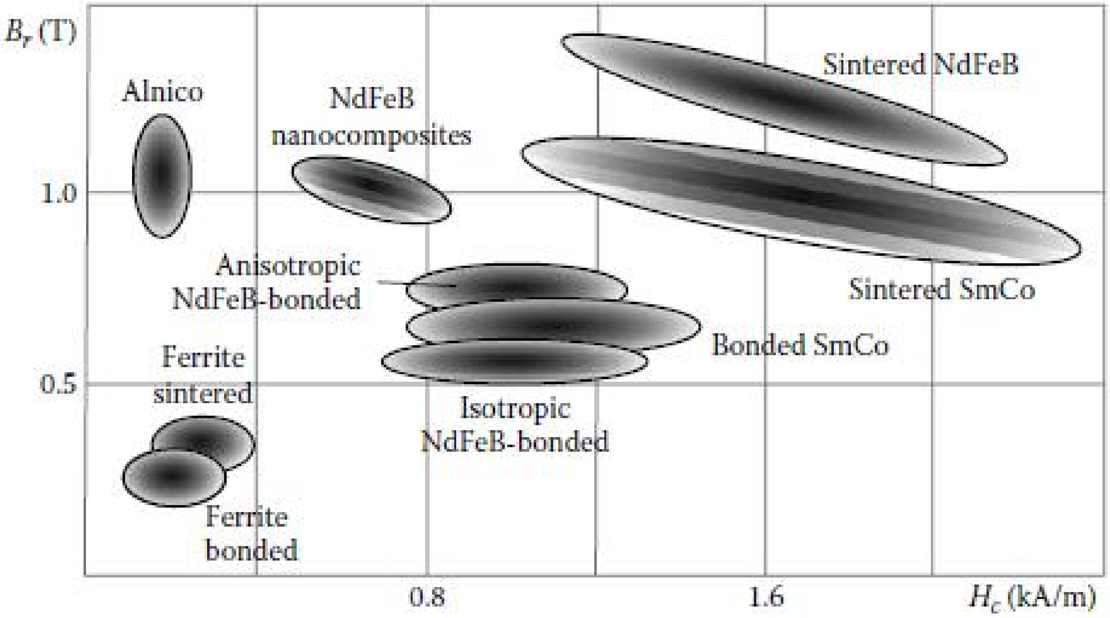
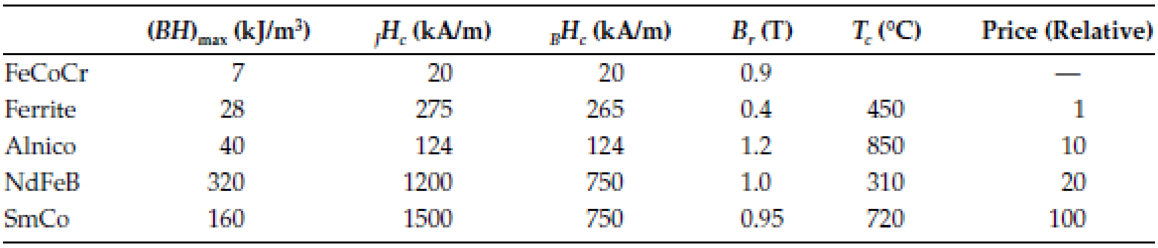


Figure 13 Comparison of the main hard magnetic materials [30]

Historically, as the first hard magnetic materials, simply different kinds of steel were used. In 1917, in Japan, cobalt steel (Fe55Co35W7Cr2C0.6) known as Honda alloy was developed. In 1931, also in Japan, Mishima invented the Alnico alloy (Fe58Ni30Al12), which gave better performance in comparison with steel. Recently, cobalt steel has practically vanished from the market as a material for permanent magnets. The table below presents parameters of the main hard magnetic materials and the figure below is market segmentation of permanent magnet materials.

Table 6 Properties of Main Hard magnetic materials



	$(BH)_{max}$ (kJ/m³)	$_JH_c$ (kA/m)	$_BH_c$ (kA/m)	B_r (T)	T_c (°C)	Price (Relative)
FeCoCr	7	20	20	0.9		—
Ferrite	28	275	265	0.4	450	1
Alnico	40	124	124	1.2	850	10
NdFeB	320	1200	750	1.0	310	20
SmCo	160	1500	750	0.95	720	100

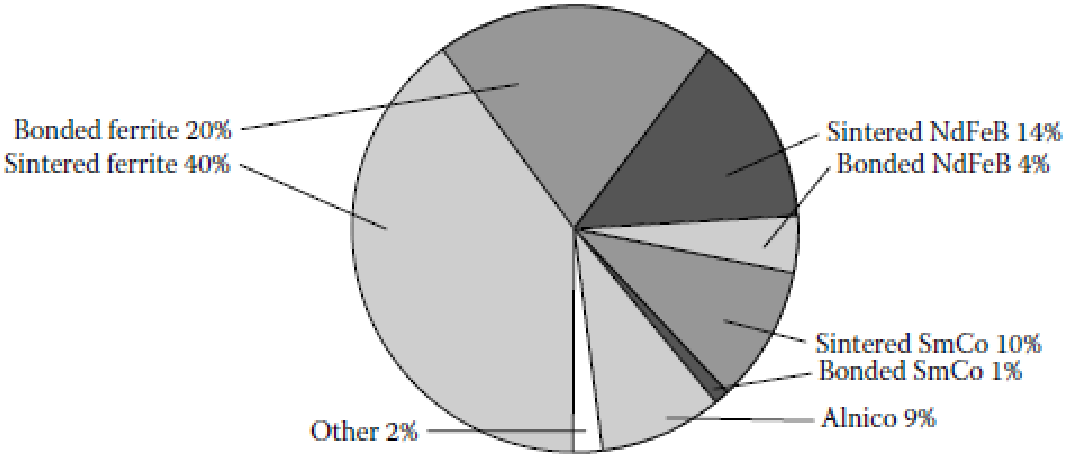


Figure 14 Permanent magnet market [30]

From the data presented in Figure 10, hard magnetic ferrites are winner.

The relationship of $B = f(H)$ was the evaluation of magnetic materials. Recently, this relation is commonly substituted by $J = f(H)$ as more reliable and describing physics of the magnetic phenomena. Only for extremely large H values, the differences can see in the soft magnetic materials. In the case of hard magnetic materials, hysteresis $B = f(H)$ is significantly different than $J = f(H)$ (Figure 15) and therefore we need to distinguish between coercivity for the $B(H)$ loop known as *BHc* and coercivity for the $J(H)$ loop known as *JHc*. The coercivity *JHc* is usually larger than *BHc* and the difference is a measure of internal possibility of material to store the magnetic energy. [30]

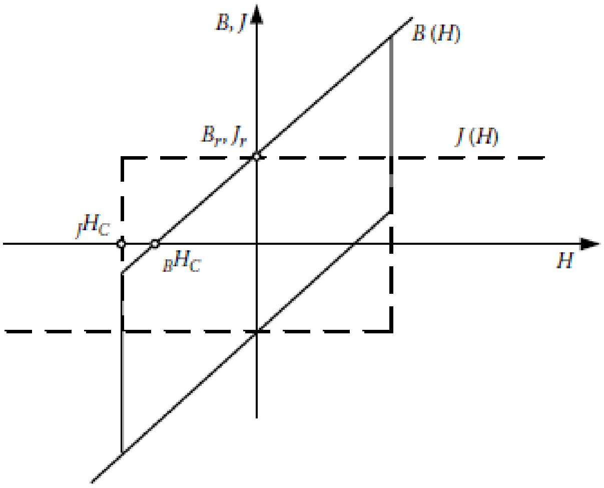


Figure 15 Ideal B(H) and J(H) hysteresis loops. [30]

2.2.2. Rare-Earth Materials for Magnetic Applications

The use of rare earth elements or oxides has resulted in significant improvements in the performance of industrial, commercial, medical, space and military applications, including efficiency, longevity, and reliability, in addition to a considerable reduction in the weight and size of components and/or overall systems. These improvements are strictly due to the unique chemical, electromagnetic, and magnetic properties of rare earth materials.

Rare earth materials have different names in the industry such as rare earth elements, rare earth metals and rare earth oxides. Essentially, they are classified into two distinct categories: light rare earth elements and heavy rare earth elements. They compose of 17 chemical elements. The important one according to our discussion is Neodymium and closest one to it which is Samarium atomic properties are listed in the table below.

Table 7 Rare-Earth Materials

Element (Symbol)	**Atomic Weight**	**Atomic Number**	**Valance**
Neodymium (Nd)	144	60	3
Samarium (Sm)	150	62	2, 3

2.2.2.1. Rare Earth Metals Properties and Applications

High reactivity is the most important factor in rare earth materials. They either react with or dissolve most materials at sufficiently high temperature and it can create problems. Application of rare earth materials generally are chemical properties due to essentially identical outer electronic configuration of their atoms. For this purpose, mixed rare earth compounds obtained in anhydrous state by the first ore processing techniques are sufficient.

The metallurgical applications of rare earth metals and alloys from a sizeable industrial outlet. The main application areas summarized in table below. [31]

Table 8 Metallurgical applications of Rare Earths

Areas of Applications	***Brief Details***
Cast Iron	Cerium or misch metal as inoculant to modify the graphite morphology from flakes to nodular
Steels, High strength low alloy steels and steels for fatigue intensive applications (axles, bearings, rail steels)	Misch metal or rare earth silicon alloy for controlling shapes of sulphide inclusions and thereby improving transverse impact strength
Copper alloys	Yttrium or misch metal for improving the oxidation resistance of copper and elimination of hot tearing in leaded brasses
Magnetic alloys	Alloying with 1-3% mish metal reduces the microporosity
Aluminium alloys	Misch metal addition improves tensile strength, heat resistance, vibration resistance and corrosion resistance
Permanent magnet alloys for producing magnets of high coercivity and high energy products	AB type where A is rare earth metal and B is cobalt. These are either cast or fabricated by powder metallurgy routes

2.2.2.2. Preparation of Permanent Magnet Alloys

The Permanent Magnets need powdered form. These alloys can be produced by a variety of methods like direct melting of the constituents by arc or induction melting, by electrodeposition or by reduction-diffusion method. Arc melting and electrodeposition are generally not practiced because of higher losses and requirement of repeated melting. In electrodeposition the control of composition is rather difficult. Commercial production of these alloys are, therefore, accomplished either by direct induction melting of the constituent metals or by reduction-diffusion process. In the former case, care is taken in handling the metals to avoid contamination. In the second phase, the rare earth oxide, cobalt and cobalt oxide and calcium are thoroughly blended, compacted an the compacts charged in a suitable container, which is then placed in a resistance furnace. The reduction takes place for 2-3 hours at 1100-1200 C in hydrogen atmosphere. The reduced powder prior to aqueous processing is exposed to moist nitrogen for disintegration. The alloy powder so produced can then be fabricated by powder metallurgy methods and magnetized to produce permanent magnets with high Curie temperature, high coercivity and high energy product. [32]

3. COMMON MATERIALS USED IN THE VEHICLES

3.1. Pure Iron- Fe

3.1.1. Set of Properties, where it is used, what purpose

Pure iron has excellent magnetic properties like large saturation polarization, low coercivity, and high permeability. But only pure iron shows this combination: even small quantities of impurities cause significant deterioration of magnetic properties. In practice, such extremely pure material is expensive and possible to use only in laboratory.

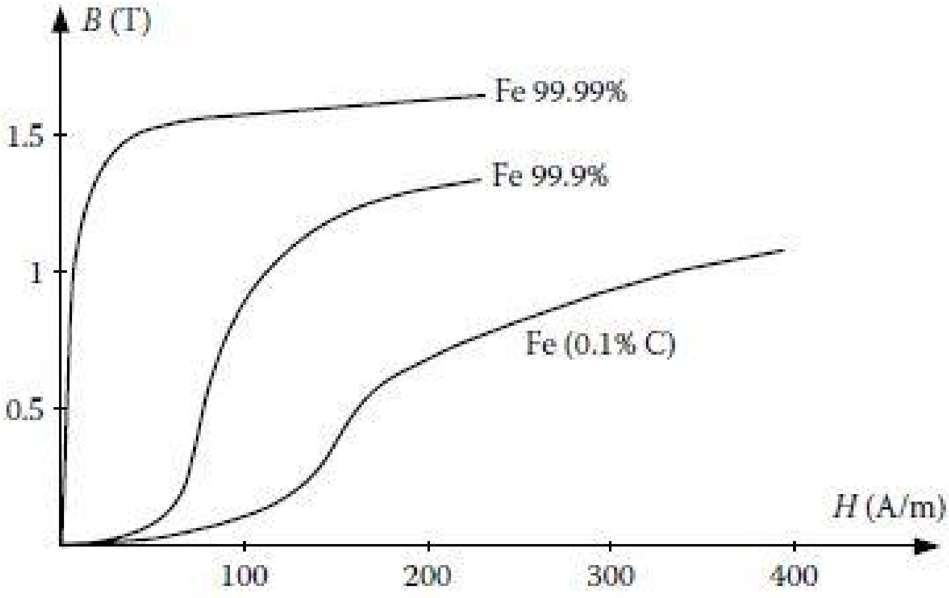


Figure 16 Magnetization curves of iron. [30]

Commercially available pure iron has much smaller permeability and larger coercivity Because impurities such as C, Mn, P, S, N, and O impede the domain wall motion. By annealing such material in hydrogen at 1200°C–1500°C, it is possible to remove most of these impurities, but such process is also quite expensive.

Pure iron has also low resistivity. Such good conductivity causes large eddy current loss and practically precludes pure iron from AC application.

3.1.2. Phase Diagram

The figure below presents the part of phase diagram of Fe-C alloys. Iron exists in two allotropic forms: α-Fe (ferrite Fe-C) ferromagnetic body-cantered cubic and γ-Fe (austenite Fe-C) paramagnetic face-cantered cubic. Above 0.008% of C in ferrite appears as impurity cementite (iron carbide, Fe3C) that above 210°C is nonmagnetic. Transition between α-Fe and γ-Fe is at 910°C, † but also ferrite is paramagnetic above Curie temperature 768°C.

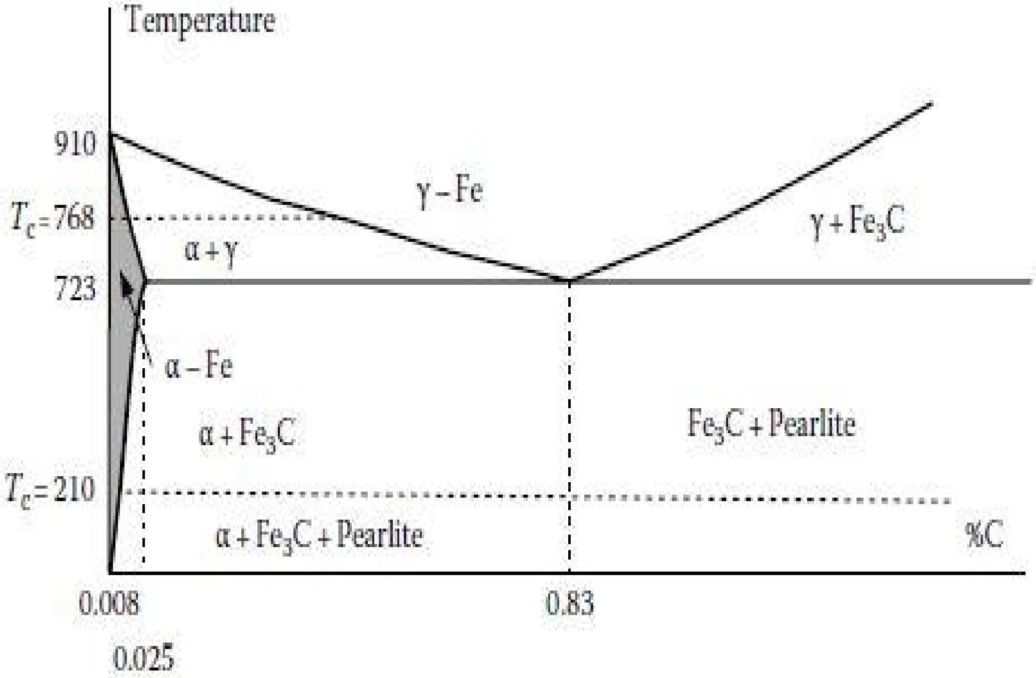
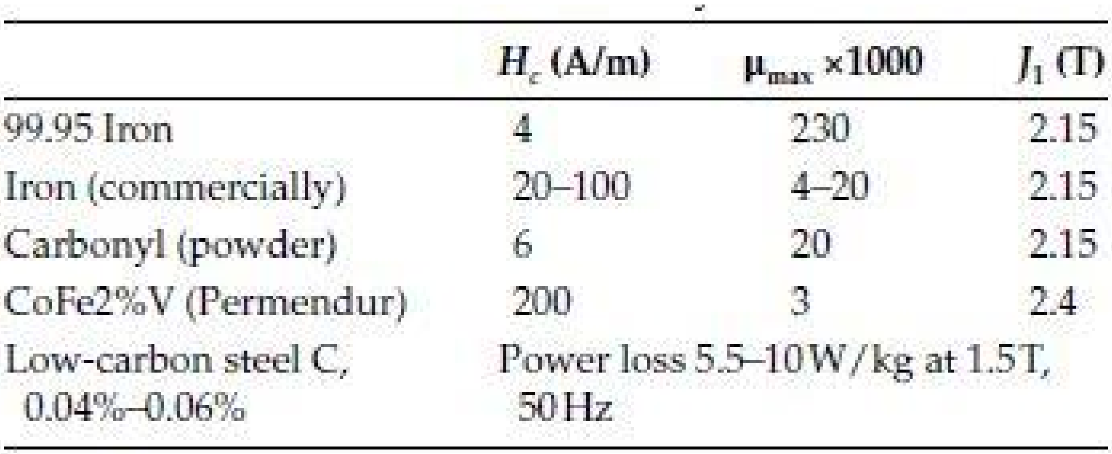


Figure 17 Iron-carbon phase diagram [30]

Especially important are Fe-Co-based alloys Fe50Co50 (known as Permendur) that exhibit the largest possible saturation polarization *JS* = 2.46 T and very high Curie temperature (*Tc* = 930°C). To improve mechanical properties of Fe-Co alloy (and increase resistivity ρ = 40 μΩ cm), a small part of vanadium is added: Fe49Co49V2. The alloy Fe49Co49V2 has very high Curie temperature (*Tc* = 950°C) (pure cobalt has *Tc* = 1130°C). The table below collects magnetic properties of iron and some of its alloys. [30]

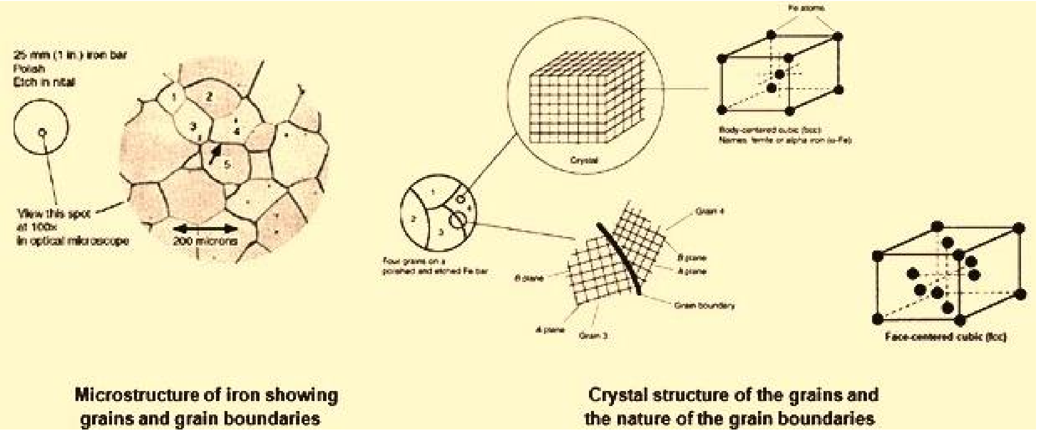
Table 9 Magnetic properties of iron



	H_c (A/m)	μ_{max} ×1000	J_1 (T)
99.95 Iron	4	230	2.15
Iron (commercially)	20–100	4–20	2.15
Carbonyl (powder)	6	20	2.15
CoFe2%V (Permendur)	200	3	2.4
Low-carbon steel C, 0.04%–0.06%	Power loss 5.5–10 W/kg at 1.5 T, 50 Hz		

3.1.3. Microstructure

The individual regions, such as those numbered 1 to 5, are called iron grains, and the boundaries between them, such as that between grains 4 and 5 highlighted with an arrow, are called grain boundaries. The average size of the grains is quite small. In the figure at the 100× magnification, a length of 200 μm is shown by the arrow so labelled. The average grain diameter for this sample has been measured to be 125 microns. Although a small number, this grain size is much larger than the grain size of most commercial irons. For a comparison, the thickness of aluminium foil and the diameter of a hair are both approximately 50 microns.



Microstructure of iron showing grains and grain boundaries

Crystal structure of the grains and the nature of the grain boundaries

Figure 18 Microstructure of pure iron showing in grains, grain boundaries and crystal structure. [33]

In pure iron the basic building blocks are the individual atoms of iron (Fe) atoms. The grains shown in the figure are called crystals and they are made up of atoms, all of the atoms are uniformly arranged in layers. [33]

3.1.4. Process of Iron

3.1.4.1. Laboratory Routes

For a few limited purposes when it is needed, pure iron is produced in the laboratory in small quantities by reducing the pure oxide or hydroxide with hydrogen or forming iron pentacarbonyl and heating it to 250 °C so that it decomposes to form pure iron powder. Another method is electrolysis of ferrous chloride onto an iron cathode

3.1.4.2. Main Industrial Route

Nowadays, the industrial production of iron or steel consists of two main stages. In the first stage, iron ore is reduced with coke in a blast furnace, and the molten metal is separated from gross impurities such as silicate minerals. This stage yields an alloy—pig iron—that contains relatively large amounts of carbon. In the second stage, the amount of carbon in the pig iron is lowered by oxidation to yield steel. Other metals can be added at this stage to form alloy steels.

3.1.4.3. Blast furnace processing

The blast furnace is loaded with iron ores, usually hematite Fe2O3 or magnetite Fe3O4, together with coke. Air pre-heated to 900 °C is blown through the mixture, in sufficient amount to turn the carbon into carbon monoxide. This reaction raises the temperature to about 2000 °C The carbon monoxide reduces the iron ore to metallic iron. Some iron in the high-temperature lower region of the furnace reacts directly with the coke. A flux such as limestone (calcium-carbonate) or dolomite (calcium-magnesium carbonate) is also added to the furnace's load. Its purpose is to remove silicaceous minerals in the ore, which would otherwise clog the furnace. The heat of the furnace decomposes the carbonates to calcium oxide, which reacts with any excess silica to form a slag composed of calcium silicate CaSiO3 or other products. At the furnace's temperature, the metal and the slag are both molten. They collect at the bottom as two immiscible liquid layers (with the slag on top), that are then easily separated. The slag can be used as a material in road construction or to improve mineral-poor soils for agriculture.

3.1.4.4. Steelmaking

In general, the pig iron produced by the blast furnace process contains up to 4–5% carbon, with small amounts of other impurities like sulphur, magnesium, phosphorus, and manganese. The high level of carbon makes it relatively weak and brittle. Reducing the amount of carbon to 0.002–2.1% by mass-produces steel, which may be up to 1000 times harder than pure iron. A great variety of steel articles can then be made by cold working, hot rolling, forging, machining, etc. Removing the other impurities, instead, results in cast iron, which is used to cast articles in foundries; for example stoves, pipes, radiators, lamp-posts, and rails. Steel products often undergo various heat treatments after they are forged to shape. Annealing consists of heating them to 700–800 °C for several hours and then gradual cooling. It makes the steel softer and more workable. [34]

3.2. Iron Silicon Fe-Si

3.2.1. Set of Properties, where it is used, what purpose and composition

The Fe-Si sheets are currently the most used material in the realization of electric motors because they offer a relatively low cost and excellent magnetic properties (low loss, high permeability, high saturation induction, low coercive field). It has been generally used in electromagnetic devices, particularly magnetic cores for motors, transformers, and precision control devices. It is known to have excellent soft magnetic properties, such as high saturation magnetization, nearly zero magnetostriction, low iron loss in medium and high frequency. In addition, this material has a good punch ability and relatively high thickness (0.50 and 0.65 mm). In high-frequency applications to limit the power losses, Fe-Si sheets with a reduced thickness (0.2 mm and 0.3 mm) are used. Among various metal cores, Fe-Si alloy powders have been considered to be one of the most suitable candidates due to low price and excellent soft magnetic properties. To obtain powder cores with good permeability and high magnetic flux density, the density of the cores must be close to the theoretical value. However, although high Si content in Fe-Si alloy improve its high frequency characteristics and soft magnetic properties, high Si content of Fe-Si powders makes it difficult to obtain compacts with high density. Silicon steels containing about 3.0 wt% Si are widely used as core materials in transformers, magnetic amplifiers and many other electronic devices. Also, at about 6.5 wt% Si, magneto-striction (λ) and crystalline anisotropy (K) can be optimized to achieve a lower core loss due to the higher permeability and lower coercivity (Hc) of the composition. Therefore, the alloys with Si content higher than ~4 wt% become too brittle to be processed by the conventional rolling process at room temperature. A number of researchers have reported that this can be overcome by using silicon-iron alloy powder cores. [12] [35] [36] [37]

Adding approximately 6.5wt% Si to Fe results in near-zero magnetostriction, near-zero magneto crystalline anisotropy and high electrical resistivity. However, this amount of Si addition also causes material embrittlement and thus makes the alloy problematic to process using traditional subtractive or formative methods. [38]

If we compare the different composition of Fe-Si material, we will obtain some different results. When the material which composed of Fe-3 wt%Si compared with the material which composed of Fe-6 wt%Si, the dc magnetic property of Fe-3.0 wt% Si powder core was higher than that of the Fe-6.5 wt% Si powder core. This may be due to the optimization of the insulation layer as well as the high magnetization and green density of Fe-3.0 wt% Si alloy. In order to understand the behaviour of the increasing dc magnetic property, magnetizations were obtained for Fe-3.0 wt% Si alloy that were higher than Fe-6.5 wt% Si, as shown in the figure below.

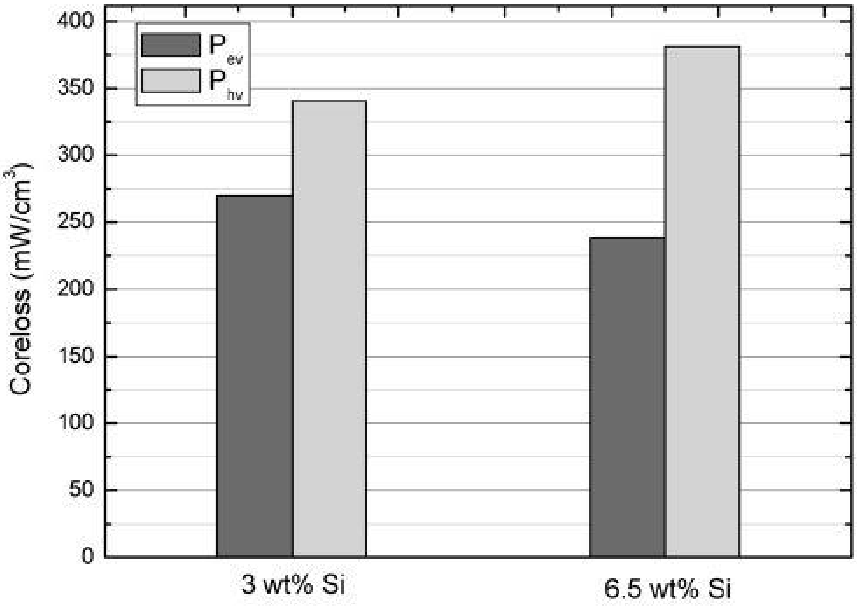


Figure 19 Eddy Current loss, hysteresis loss of 3.0 wt%, 6.5 wt% Fe-Si powder cores [39]

The figure below shows the frequency dependency of the permeability of Fe-3.0 wt% Si powder cores, the powder of which was annealed at 900oC for 2 hours in an N2 gas atmosphere. An effective permeability, μeff of 65 is maintained up to 300 kHz. From the above results, it can be concluded that Fe-3.0 wt% Si powder cores can be commercialized. [39]

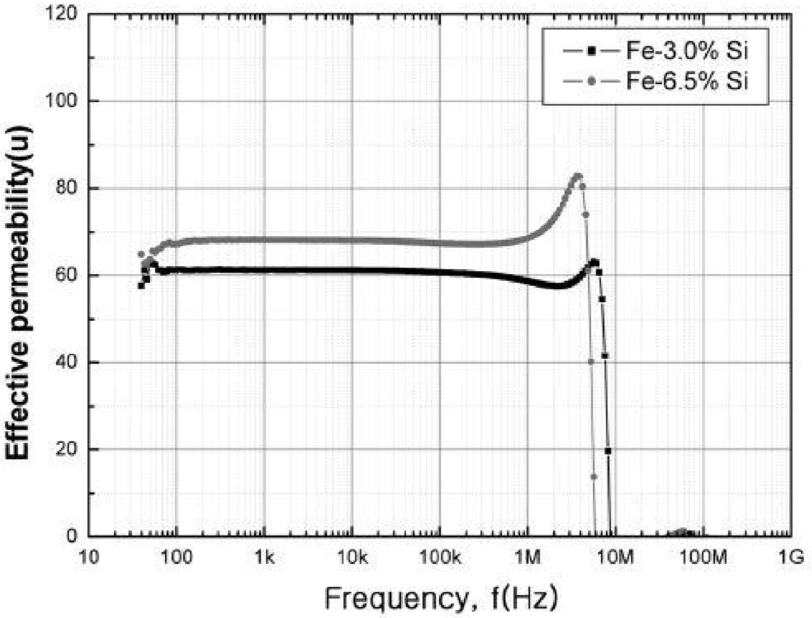


Figure 20 Effective permeability of Fe-3.0 wt% Si powder cores as a function of frequency [39]

3.2.2. *Addition of Si and Al*

One of the most important drawbacks of pure iron is its relatively low resistivity and hence large eddy current loss. Figure 22 presents the resistivity of different iron alloys. We can see that good candidates for resistivity improvement are silicon and aluminium. Addition of silicon influences also saturation polarization and Curie temperature.

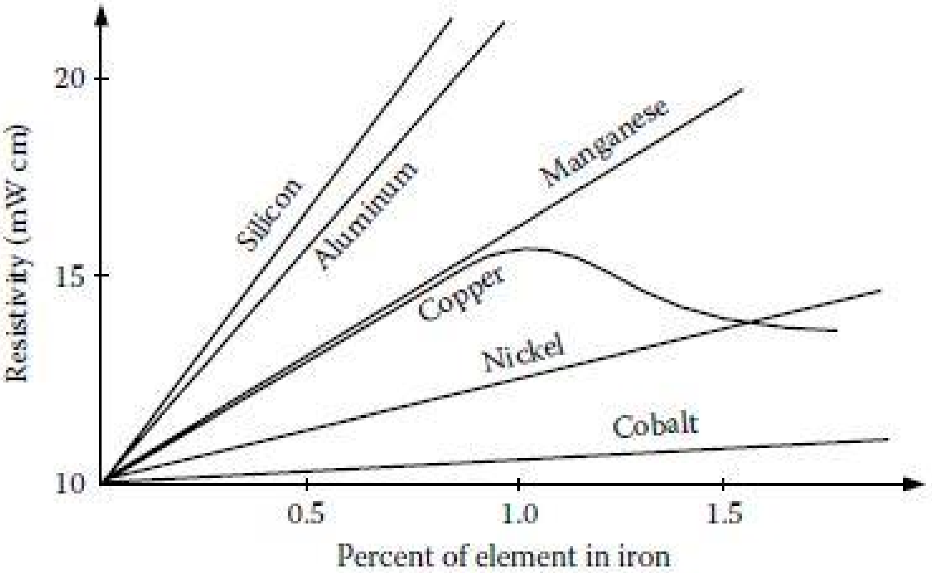


Figure 21 Resistivity of different iron alloys [30]

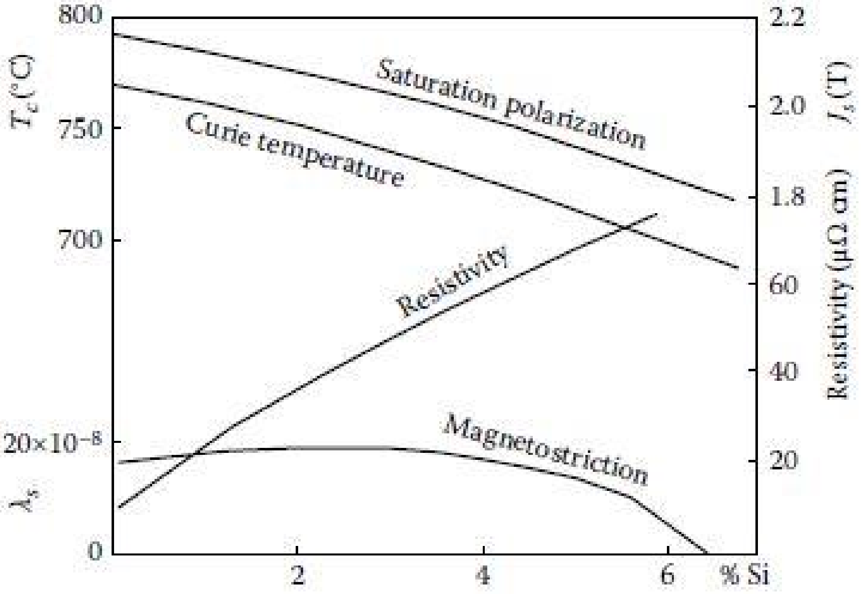


Figure 22 Magnetic and electric parameters as a function of silicon content [30]

From figure above, the best would be 6.5% content of Si because resistivity increases almost sevenfold, and the material is non-magneto strictive. Unfortunately, this material is very hard and brittle, what is disadvantageous in rolling process as well as in punching the final product. In practice, punching can be carried out only for the steel with up to 3%–4% silicon content. Large content of Si causes also decrease of saturation polarization as well as the permeability. Therefore, the GO silicon steel is manufactured mostly often with 2.7%–3.3% of silicon although also 6.5% Fe-Si is offered in the market (in small volume and for higher price).

3.2.3. Microstructure

The figure below presents part of a phase diagram of iron–silicon. The transition between α-Fe and γ-Fe is at 911°C. For silicon content higher than 1.86%, this transition no longer takes place, and it is possible to anneal the material to high temperatures for removal of parasitic impurities. The most unwanted components in Fe-Si steel are carbon, oxide, sulphur, and nitrogen because even small amounts of this element cause increase of hysteresis loss. Therefore, the starting material should be as pure as possible and after manufacturing, the content of these elements can be smaller than 10 ppm.

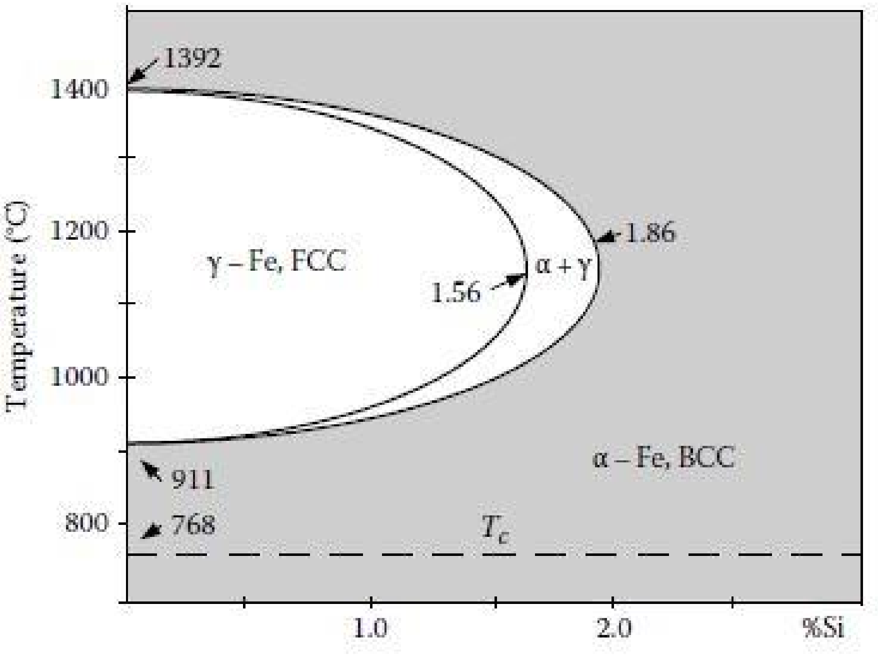


Figure 23 Iron-silicon Phase diagram [30]

Figure 25 presents the example of grain structure of GO electrical steel. In a grain-oriented steel, we profit from its anisotropic properties of the fact that the iron crystal have the best magnetic properties in "easy" direction. Therefore, the main effort is made to obtain the best Goss texture with relatively large grains ordered in one direction. Figure 26 presents dependence of flux density and loss on the tilt angle. Surprisingly, the minimum of the loss occurs when the grain is slightly misoriented from the perfect direction. The best results are obtained for the grain orientation of about 2°.

Figure 24 The example of grain structure of GO steel: in the left part an incompletely recrystallized line is visible [30]

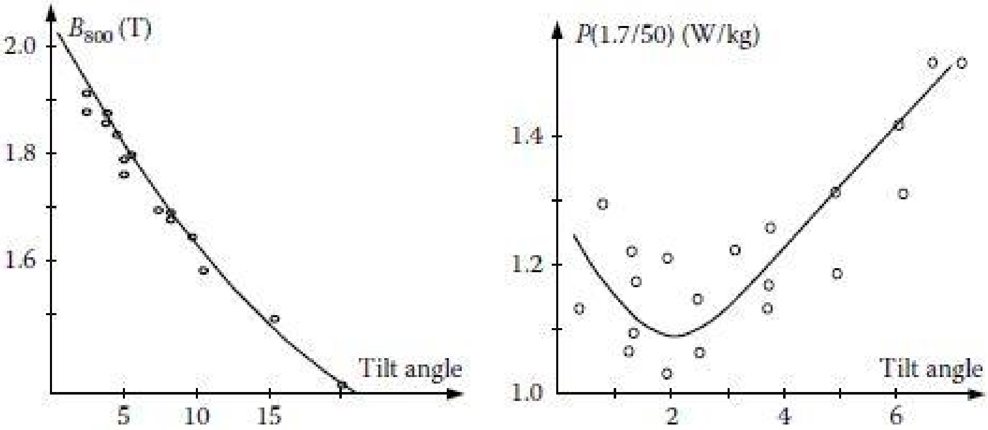


Figure 25 Flux density and core loss versus tilt angle [30]

Perfectly oriented grains (0°) have wider spaced of the 180° domain walls than for a tilt angle 2°. This domain width strongly influences excess loss. The domain wall spacing can be significantly decreased by applying a stress, which is one of the methods known as a domain refinement. After the first annealing in production process, the grain dimensions are only around 0.02 mm. After second annealing (secondary recrystallization), the Goss-oriented grains grow through the thickness of the sheet to diameter 3–7 mm with average misorientation of around 6°. Theoretically, as larger grains as better, but measurements of loss versus grain dimensions did not confirm such a simple relationship.

Excellent properties along rolling direction are advantageous when we can guarantee that magnetization is applied only in this direction. But this advantage can be a problem when a part is magnetized not exactly in the rolling direction (e.g., corners of a square core). In such a case, we must expect significant deterioration of the material performance. The figure below presents the magnetization curve and losses determined for various directions of magnetization.

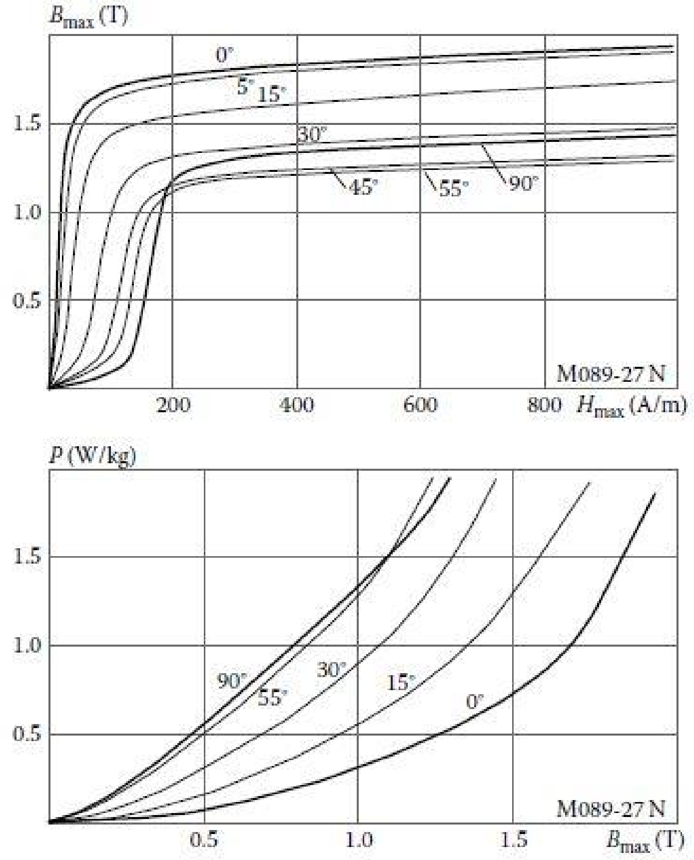


Figure 26 Properties of GO Fe-Si steel in different directions of magnetization with respect to rolling direction [30]

The figure below presents the magnetization curves of typical NO steel determined for various angles of magnetization. It should be noted that this material is not purely isotropic but in comparison with grain-oriented steel, the change of properties with the change of direction of magnetization are acceptably small. That is why in rotating machines the NO material is much more often used than the grain-oriented steel.

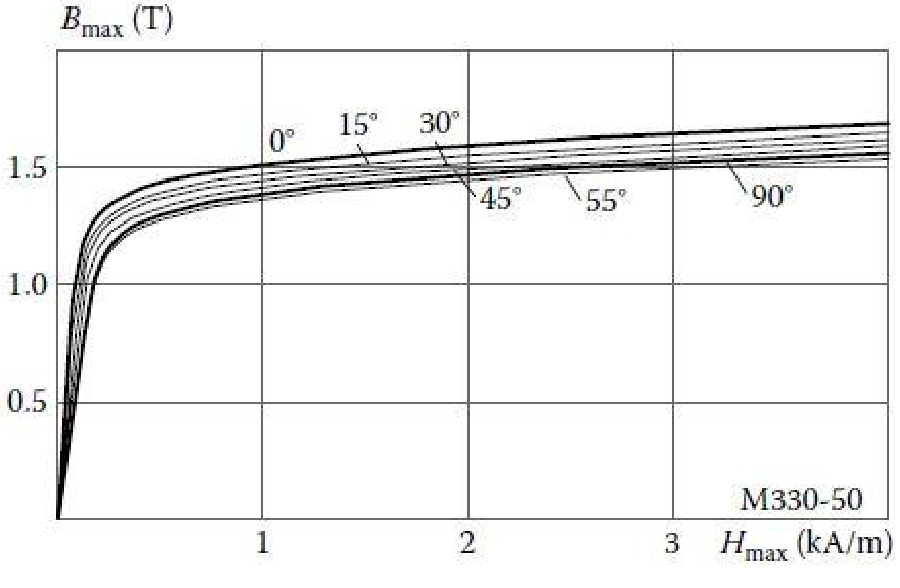


Figure 27 Magnetization curves of typical non-oriented steel determined for various angle of magnetization [30]

3.2.4. Classification

Electrical GO steel is classified according to international standards based on the power loss. European standard EN 10107 uses the following nomenclature for the steel grades:

- First letter M for electrical steel.
- Three digits after the first letter denote value of specific loss measured at 1.5 or 1.7 T.
- Two further digits represent the thickness. d. Last letter describes type of material: N, normal (loss measured at 1.5 T), S, reduced loss (loss at 1.7 T); P, high permeability (loss at 1.7 T). For example, M097-30N means electrical steel (M) of normal grade (N) with material thickness 0.3 mm (30) and power loss at 1.5 T not exceeding 0.97 W/kg.

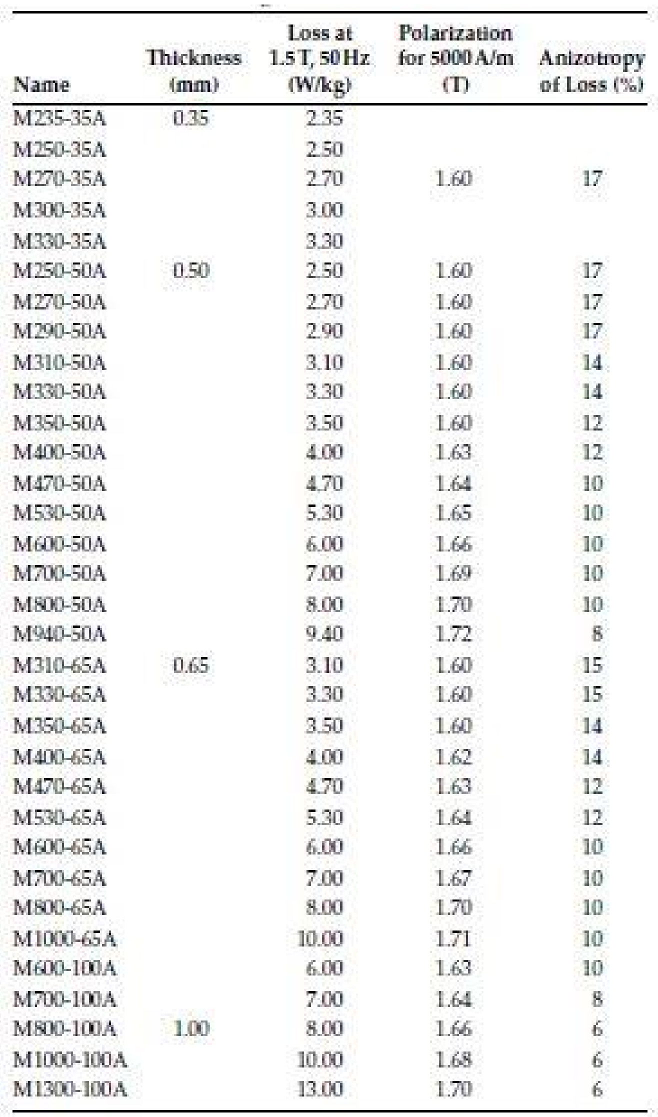
NO Fe-Si steel is classified by international standards in a similar way as the GO Fe-Si steel, mainly according to the power loss. Table 10 presents the classification according to European Standard EN 10106. Standards determine maximum anisotropy of loss described as:

$$T = \frac{P_1 - P_2}{P_1 + P_2} x100$$

Where,

- $P1$ is the loss in a sample cut perpendicular to the rolling direction
- $P2$ is the loss in a sample cut parallel to the rolling direction

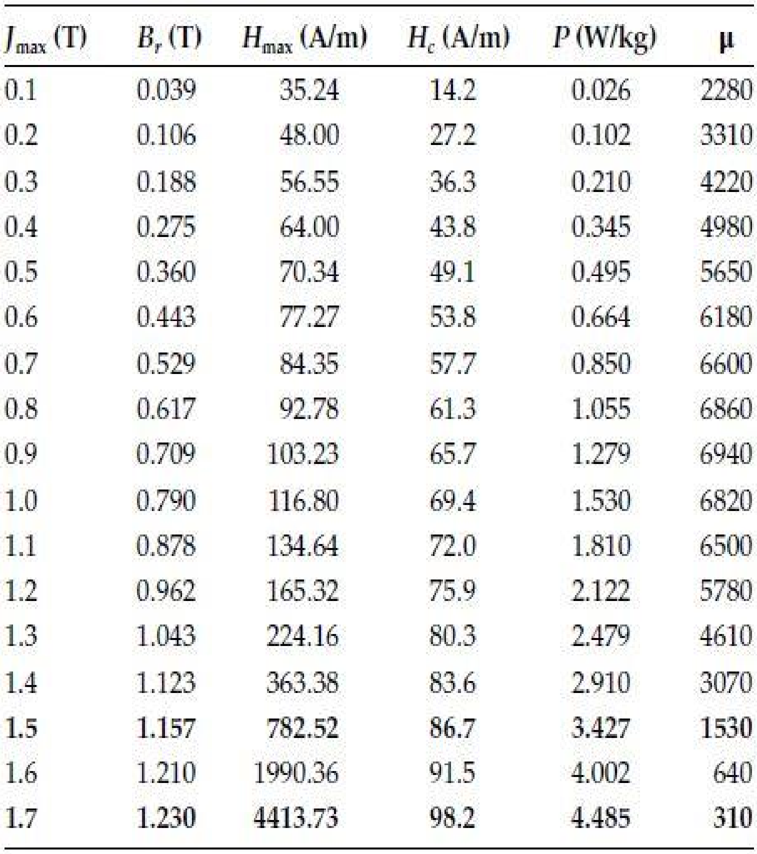
Table 10 Classification of fully processed NO electrical steel according to standard EN10106



Name	Thickness (mm)	Loss at 1.5 T, 50 Hz (W/kg)	Polarization for 5000 A/m (T)	Anizotropy of Loss (%)
M235-35A	0.35	2.35		
M250-35A		2.50		
M270-35A		2.70	1.60	17
M300-35A		3.00		
M330-35A		3.30		
M250-50A	0.50	2.50	1.60	17
M270-50A		2.70	1.60	17
M290-50A		2.90	1.60	17
M310-50A		3.10	1.60	14
M330-50A		3.30	1.60	14
M350-50A		3.50	1.60	12
M400-50A		4.00	1.63	12
M470-50A		4.70	1.64	10
M530-50A		5.30	1.65	10
M600-50A		6.00	1.66	10
M700-50A		7.00	1.69	10
M800-50A		8.00	1.70	10
M940-50A		9.40	1.72	8
M310-65A	0.65	3.10	1.60	15
M330-65A		3.30	1.60	15
M350-65A		3.50	1.60	14
M400-65A		4.00	1.62	14
M470-65A		4.70	1.63	12
M530-65A		5.30	1.64	12
M600-65A		6.00	1.66	10
M700-65A		7.00	1.67	10
M800-65A		8.00	1.70	10
M1000-65A		10.00	1.71	10
M600-100A		6.00	1.63	10
M700-100A		7.00	1.64	8
M800-100A	1.00	8.00	1.66	6
M1000-100A		10.00	1.68	6
M1300-100A		13.00	1.70	6

Thus, the NO Fe-Si steel should be tested using two sets of samples. Table 11 presents an example of the results of measurement for a typical NO Fe-Si steel. NO Fe-Si steel is usually delivered in coated form. Various coating materials, organic or inorganic, are used. Coating plays important role because it is not only the insulating layer but also protects against oxidation, aids in punch ability, and in certain cases it can introduce tensile stress to improve the quality. [30]

Table 11 Example of results of measurements for typical NO SiFe steel Grade:M400-50AP



J_{max} (T)	B_r (T)	H_{max} (A/m)	H_c (A/m)	P (W/kg)	μ
0.1	0.039	35.24	14.2	0.026	2280
0.2	0.106	48.00	27.2	0.102	3310
0.3	0.188	56.55	36.3	0.210	4220
0.4	0.275	64.00	43.8	0.345	4980
0.5	0.360	70.34	49.1	0.495	5650
0.6	0.443	77.27	53.8	0.664	6180
0.7	0.529	84.35	57.7	0.850	6600
0.8	0.617	92.78	61.3	1.055	6860
0.9	0.709	103.23	65.7	1.279	6940
1.0	0.790	116.80	69.4	1.530	6820
1.1	0.878	134.64	72.0	1.810	6500
1.2	0.962	165.32	75.9	2.122	5780
1.3	1.043	224.16	80.3	2.479	4610
1.4	1.123	363.38	83.6	2.910	3070
1.5	1.157	782.52	86.7	3.427	1530
1.6	1.210	1990.36	91.5	4.002	640
1.7	1.230	4413.73	98.2	4.485	310

3.2.5. Processing

In short terms, the process may be described as follows: Iron ore (Fe_2O_3), quartz (SiO_2) and carbon (C), in the form of coal, coke and biocarbon, is added at the top of the furnace. Three electrodes in the furnace are heating the material. At approximately 2000˚C the carbon reacts with the oxygen in the quartz, and we are left with liquid silicon. The iron oxide in the iron ore pellets reacts with the carbon through a similar reaction and forms pure iron. Melted iron and silicon mix and is then tapped in ladles. The metal is cooled and crushed into pieces of variable size, to meet the customer's demand.

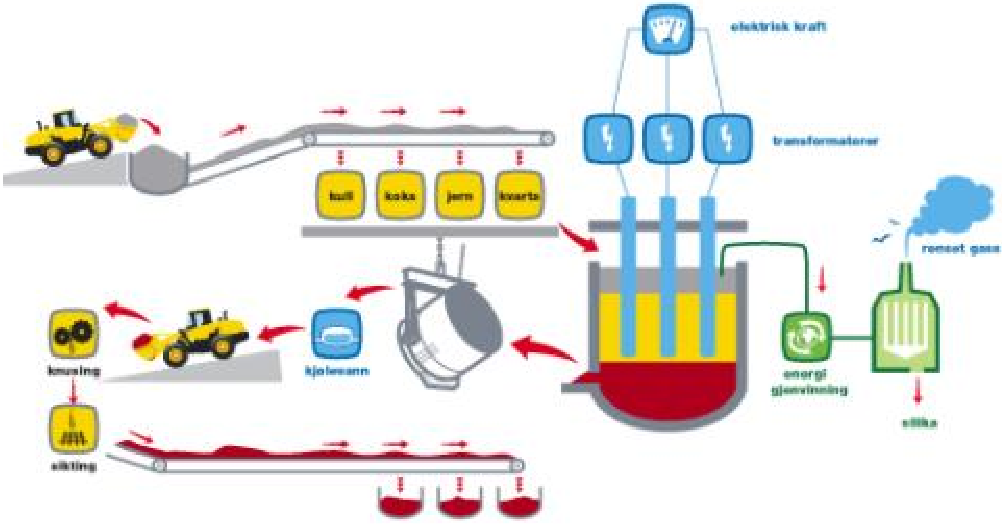


Figure 28 Process of Fe-Si [40]

On the other hand, methods for producing thin lamination of high-Si steel include melt-spinning which employs rapid quenching to avoid material embrittlement and chemical vapour deposition whereby Si is added by diffusion to previously manufactured low-S, steel lamination. For the same purpose, Selective Laser Melting technology is applying to manufactured high Si steel. In SLM, a laser-based powder-bed additive manufacturing technology, can be employed for manufacturing three-dimensional high-Si parts. [40] [38]

NO steel is delivered in one of the two possible forms: fully finished or semifinished. In the case of semifinished steel, the customer has to anneal the material after stamping. Semifinished steel is only a partly decarburized to obtain better punch ability (final decarburization is obtained in final annealing). Because it is not necessary to perform 24 h annealing for recrystallization and grain growth, the production process is much simpler (faster and therefore cheaper). During annealing, care should be taken to not allow the extra grain growth. For this reason, the duration of annealing and of cooling should be precisely controlled. The optimal grain size is around 100–200 μm.

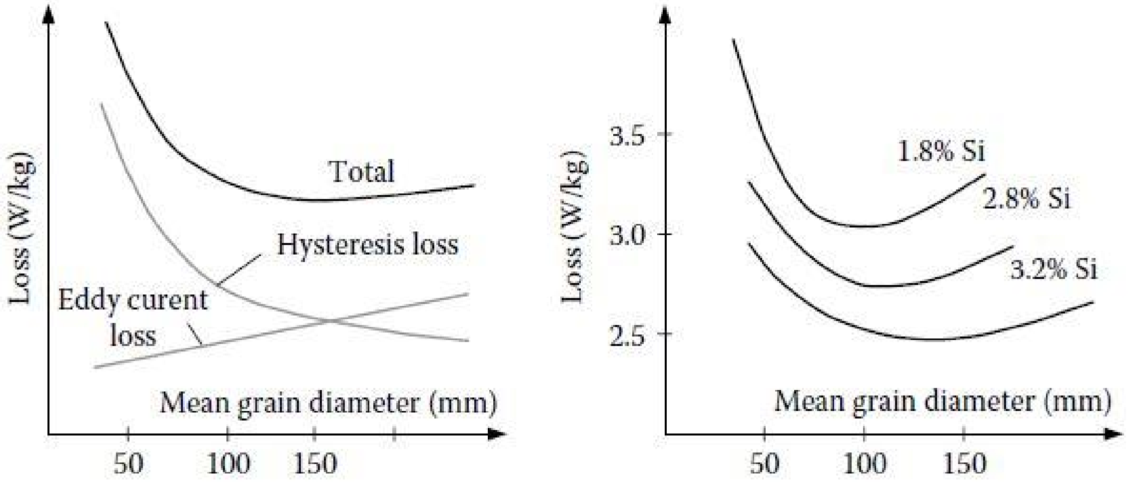


Figure 29 Influence of mean grain diameter on power loss [37]

During the production of NO Fe-Si fully processed strips, the material microstructure changes because of lamination and heating processes, while the magnetic properties are strongly influenced by the crystalline texture and grain size development. Shaping of laminated magnetic cores always implies cutting of the sheets and ensuing degradation, via localized plastic deformation, of their soft magnetic properties. The performances of fully processed NO Fe-Si laminations can be seriously impaired by the cutting operations required to form the slotted stator core of rotating machines. Some important consequences of this process affecting magnetic softness are dislocations, cracking, and grain deformation. These effects are more pronounced in the electrical machine stator teeth, and they are considered in device design as a building factor. [37]

3.3. Neodymium Iron Boron Nd-Fe-B

3.3.1. Set of Properties, where it is used, what purpose

The permanent magnets play an important role in the contemporary technology. The area of application of the hard magnetic materials grows along with the improvement of their magnetic, electrical, mechanical, and thermal properties. Permanent magnets are used, among others, in the instruments and devices for telecommunications, computer industry, as well as in the control and measurement technology. Their use gets lastly wider and wider in the electrical machines. [41] [42]

In the car industry, NdFeB material is used in different kind of electric machines in the vehicle. The figure below shows the example of usage of NdFeB material.

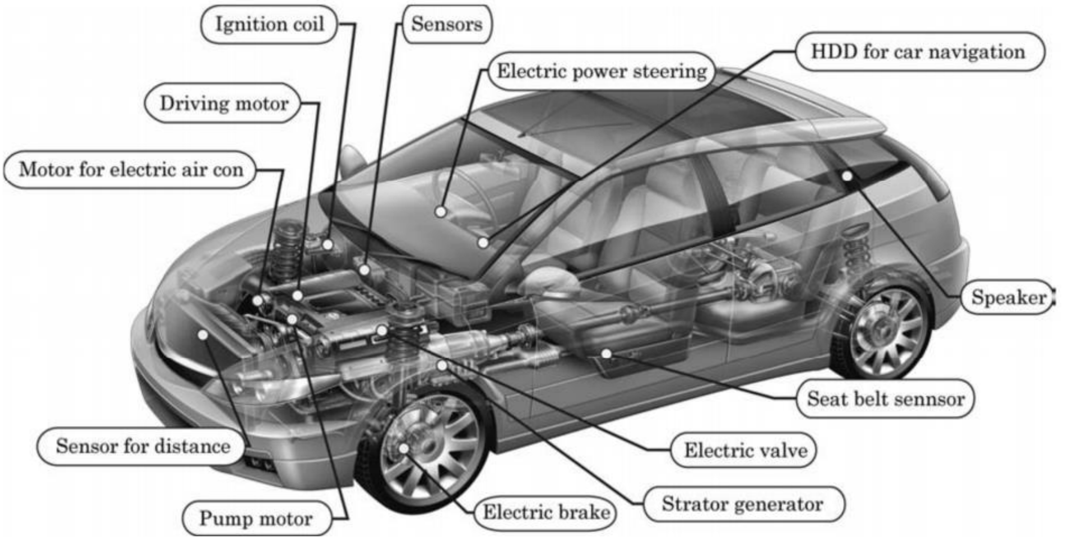


Figure 30 NdFeB material used in car parts [43]

Permanent magnets from the rare-earth material group have very good magnetic properties, but their disadvantage is a high price – researchers were looking for permanent magnets with comparable magnetic properties but less expensive. The next stage of development in the technology of manufacturing hard magnetic materials was the creation of hard magnetic materials from Nd-Fe-B alloys. This type of permanent magnets was first developed in 1984 by Sumitomo Special Materials in Japan and General Motors in USA. The good magnetic properties of intermetallic phase Nd2Fe14B are caused by ferromagnetic coupling of magnetic moments in sublattice of the rare earth group and iron. Among the advantages of the Nd-Fe-B compound is its lower price and easier access to components. These magnets are more efficient not only in their magnetic parameters and in the availability of raw materials as compared to other rare-earth magnets and traditional Alnico alloys but, in many cases, also from an economic point of view. One can observe a continuously broadening range of applications of these magnets, including those involving high temperature, corrosive, and mechanical constraints, as well as demagnetization fields. New, efficient fields of application of these magnets can be exemplified by such highly loaded products as passive radial bearings with high load-carrying capacities and velocity parameters for magnetic hangers, a series of synchronous valve actuators (brushless machines) with power varying from tens to hundreds of kilowatts, precise scanning drives, etc. To select a material for a specific practical application under more complicated operating conditions, it is necessary to consider not only its magnetic parameters but also other physical, mechanical, or chemical properties.

It is noteworthy that Nd-Fe-B type permanent magnets inherit a structure anisotropy of properties, and increased brittleness and hardness, which bring considerable difficulties in studying their physical and mechanical properties, thus requiring the development of special techniques and equipment. The determination of strength characteristics of such brittle permanent magnets has much in common with the evaluation of mechanical properties of structural ceramics. This comes from the low workability of sintered permanent magnets, as well as from relatively low resistance to crack propagation, sensitivity to stress concentrations and impact loads, and from structural inhomogeneity.

Devices made with Nd-Fe-B benefit from the high remanence and coercivity and the near-ideal loop shape of the new magnets. Consequent advantages include a higher torque for a given frame size, improved efficiency, better dynamic response and reduced weight and volume. However, there are also some difficulties: the handling and assembly of the magnetized parts of industrial drives demand special procedures; the temperature sensitivity of the coercivity requires that particular attention must be paid to the thermal aspects of any new design, and special computer-aided design techniques must be developed. [41] [42] [43]

3.3.2. Composition and microstructure and phase diagram

An NdFeB material has the following basic chemical composition: 30-32% of its weight is rare earth metals, 1% of its weight is boron, 0-3% of its weight is cobalt, and the balance is iron. There are also minor quantities of metals like copper in the alloy for metallurgical reasons. There can be different rare earth metals in the alloy. The most used metals are neodymium (Nd), dysprosium (Dy), praseodymium (Pr) and terbium (Tb). Nd and Pr are called light rare earths, while Dy and Tb are called heavy rare earths.

The table below shows chemical compositions, densities, and magnetic properties of the studied permanent magnets.

Table 12 Chemical composition and magnetic properties of the sintered Rare earth Fe-M-B magnets

Alloy code	Composition (at%)	Density (g cm^{-3})	Magnetic properties			
			B_r (T)	H_{cb} (kA m^{-1})	H_{ci} (kA m^{-1})	$(BH)_{max}$ (kJ m^{-3})
(1)	$Nd_{14}Dy_2Fe_{70{\cdot}5}Co_5B_{7{\cdot}5}$	7·45	1·10	750	1400	220
(2)	$Nd_{14{\cdot}5}Dy_{2{\cdot}5}Fe_{70}Co_5B_8$	7·50	1·05	750	1600	210
(3)	$Nd_{17}Fe_{76}B_7$	7·45	1·15	600	700	240
1	$Nd_{14}Dy_1Fe_{69{\cdot}5}Co_5Cr_2Al_1B_{7{\cdot}5}$	7·35	1·05	815	1080	215
2	idem	7·46	1·04	800	1000	210
3	idem	7·20	1·00	730	940	185
4	idem	7·60	1·05	7·25	850	190
5	$Nd_{14}Dy_1Fe_{67}Co_5Nb_3Al_2B_8$	7·30	1·05	760	1450	210
6	$Nd_{14}Dy_2Tb_2Fe_{69{\cdot}5}Co_5B_{7{\cdot}5}$	7·50	1·05	740	1600	195
7	$Nd_{13{\cdot}8}Tb_{0{\cdot}8}Fe_{72{\cdot}7}Co_5Nb_{0{\cdot}7}B_7$	7·40	1·25	800	915	250
8	$Nd_{14}Dy_{2{\cdot}5}Fe_{61}Co_{12}Al_3B_{7{\cdot}5}$	7·45	1·05	760	1200	200
9	$(Nd,Pr)_{14}Fe_{76}Co_5Al_4B_8$	7·30	1·05	740	1150	195
10	$Nd_{15}Fe_{71}Co_5Zr_1B_8$	7·40	1·15	700	800	200
11	$Pr_{16}Fe_{69}Co_5B_8$	7·35	1·16	600	700	165

The intermetallic phases of the rare earth metals (RE) and transition metals (TM) RE–TM type, since years, the very interesting materials for the permanent magnets. The magnetic hard material based on the Nd2Fe14B intermetallic phase was developed with the powder metallurgy technology and with the melt quenching method used for making metallic glasses. The magnetic properties of this phase result from the ferromagnetic coupling of magnetic moments of sublattices of the rare earth metals group and iron. Currently, the most dynamic growth is observed in the sintered neodymium hard magnetic materials group, hot compacted, upset, and composite ones. [41] [42]

For permanent magnets the most important parameters are maximum density of magnetic energy (BH)max, magnetic remanence Br, coercivity of magnetic flux density HcB, and coercivity of magnetic polarization HcJ. The more these values are the better permanent magnet is. The figure below shows metallographic photo of Nd-Fe-B powder used for preparing samples of permanent magnets. [44]

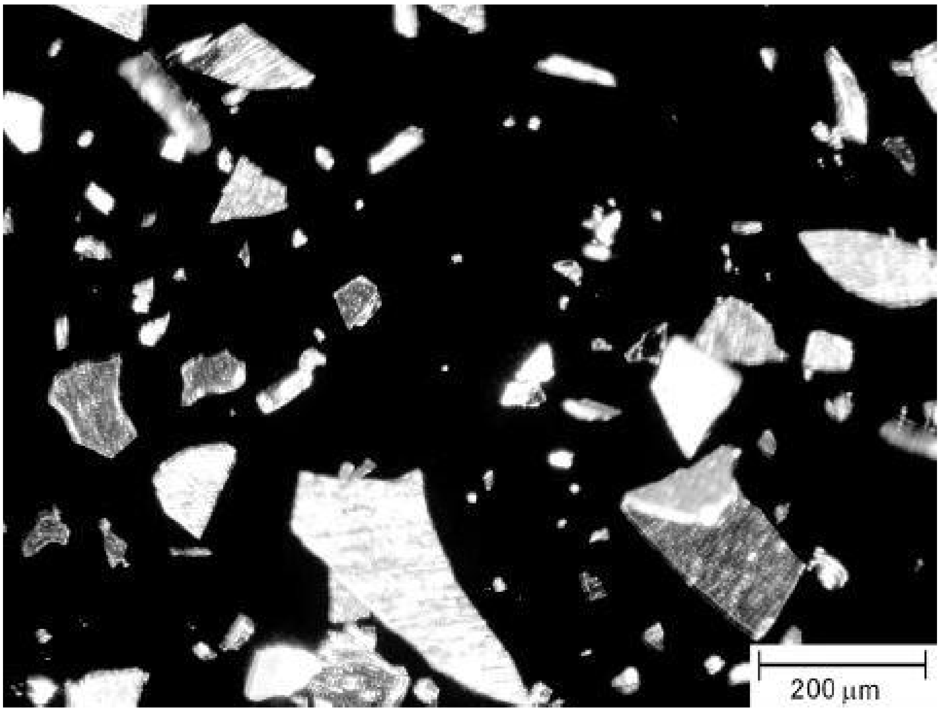


Figure 31 Grains of Nd-Fe-B powder [41]

Nd2Fe14B structure has a tetragonal crystal structure. It is largely composed of Fe which is abundant. Relatively small amount of abundant light rare earth provide anisotropy. Tetragonality is stabilised by Boron occupying only 2 volumes of %. [43]

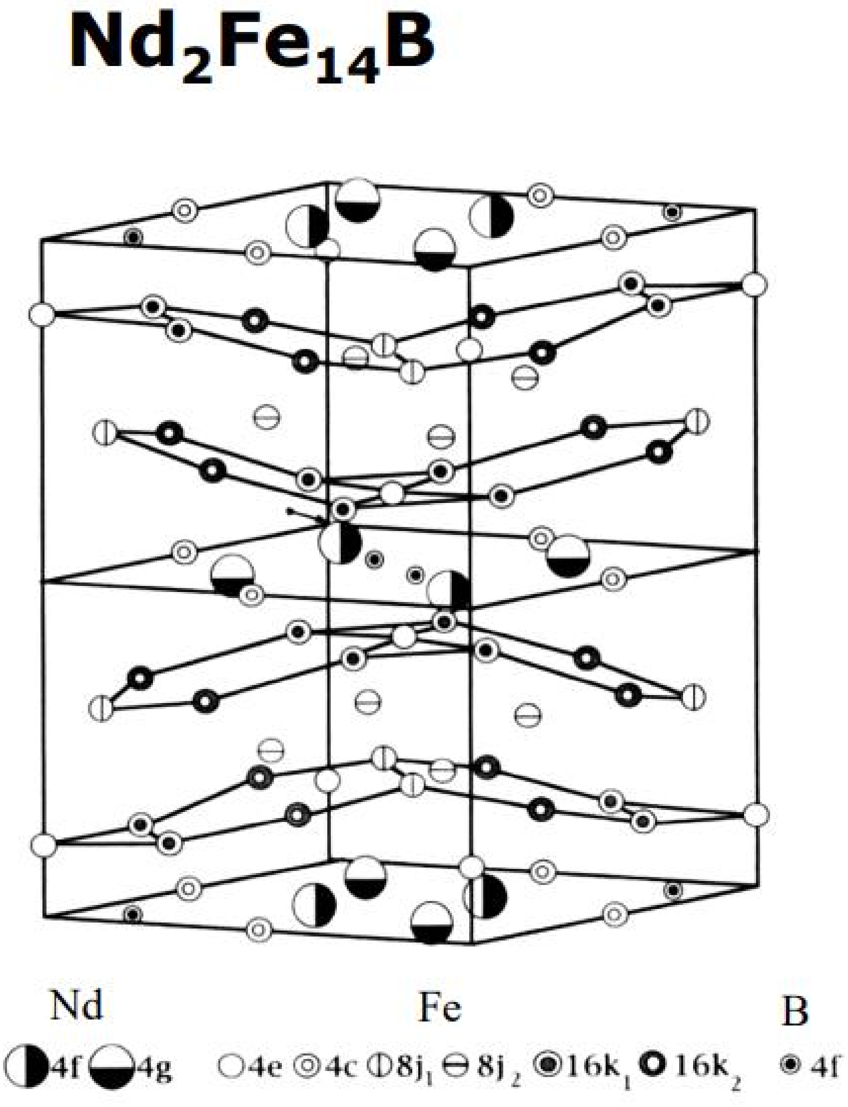


Figure 32 Microstructure of Nd-Fe-B [43]

The crystal structure and symmetry of Nd-Fe-B result from mirror symmetry in two orthogonal planes and contribute to its strong magnetic properties. The structure of Nd-Fe-B is tetragonal in structure and has space group symmetry of $p4_2$/mnm; the neodymium and iron are in parallel alignment within the sublattices. This symmetry produces a magnetization of approximately 1.6 T at room temperature and an anisotropy of resulting from the ‘mm’ symmetry through the two neodymium sites. Microstructure plays important role in the magnetic properties of Nd-Fe-B magnets. The magnetization and demagnetization can be altered by controlling the size, shape and orientation of the grains. To achieve different microstructures, three different processing techniques are currently employed powdered metallurgical methods: sintering and melt spinning and mechanical alloying. [45]

3.3.3. Effect of sintered body to material microstructure

The permanent magnet properties are strongly influenced by the microstructure of the sintered body. Some recognized relations are as follows:

- The coercive force available in the permanent magnet can be obtained in a restricted composition range near the Nd-Fe-B phase
- The most appropriate sintering temperature (1353 K) is 80 °C lower than the melting point of this compound (1433 K). The mechanism of sintering belongs to the category of the liquid phase sintering.
- The coercive force changes depending on the condition of the post sintering heat treatment [46]

Just give an example, in the Figure 30, there are example of different structure due to different temperature for sintered NdFeB materials by under Spark Plasma Sintered (SPS) process. Careful mean grain size measurement by standard interception method finds that the mean grain size grows as a function of sintering temperature and the grain size of SPS magnets is obviously smaller than that of conventionally sintered magnets as shown in the figure below**.** [47]

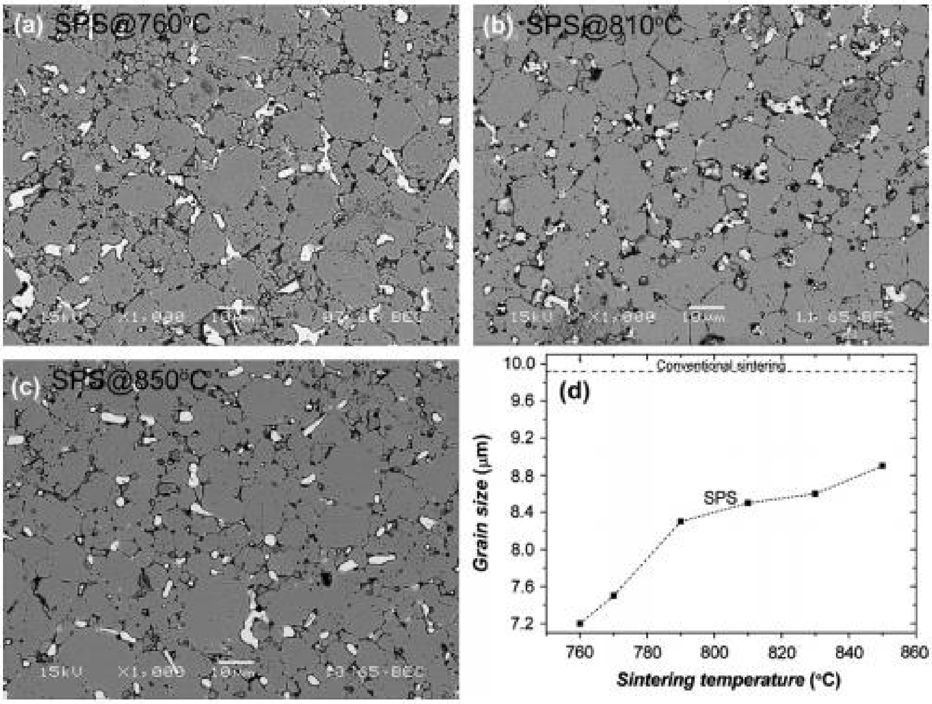


Figure 33 Microstructures of the NdFeB magnets sintered at (a) 760 C, (b) 810 C, (c) 850 C, together with (d) mean grain size as a function of SPS temperature [47]

A phase diagram around Nd2Fe14B up to ~920K is proposed in Figure 31. It is likely that, above ~920K Nd2Fe14B ternary liquid is formed as a result of the eutectic reaction between Nd2Fe14B and Nd metal.

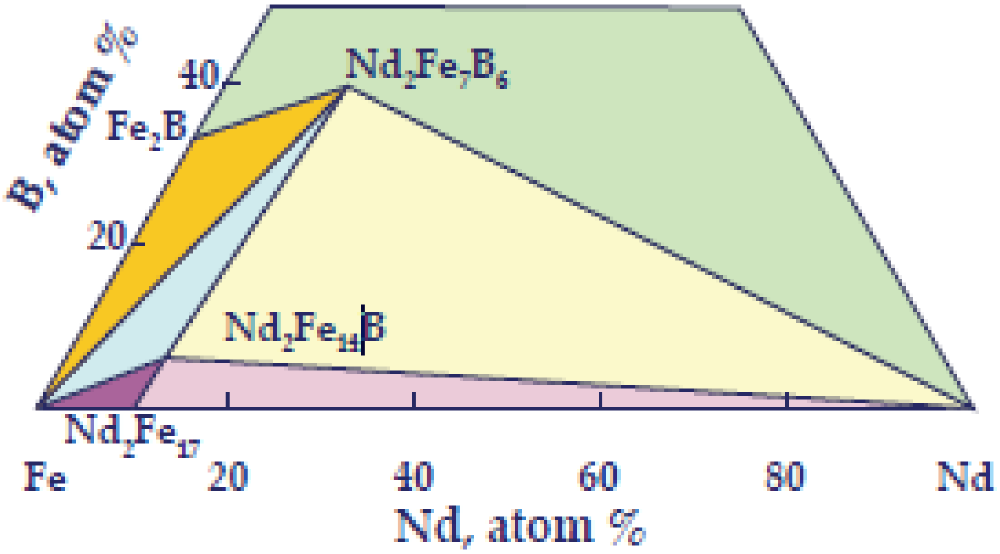


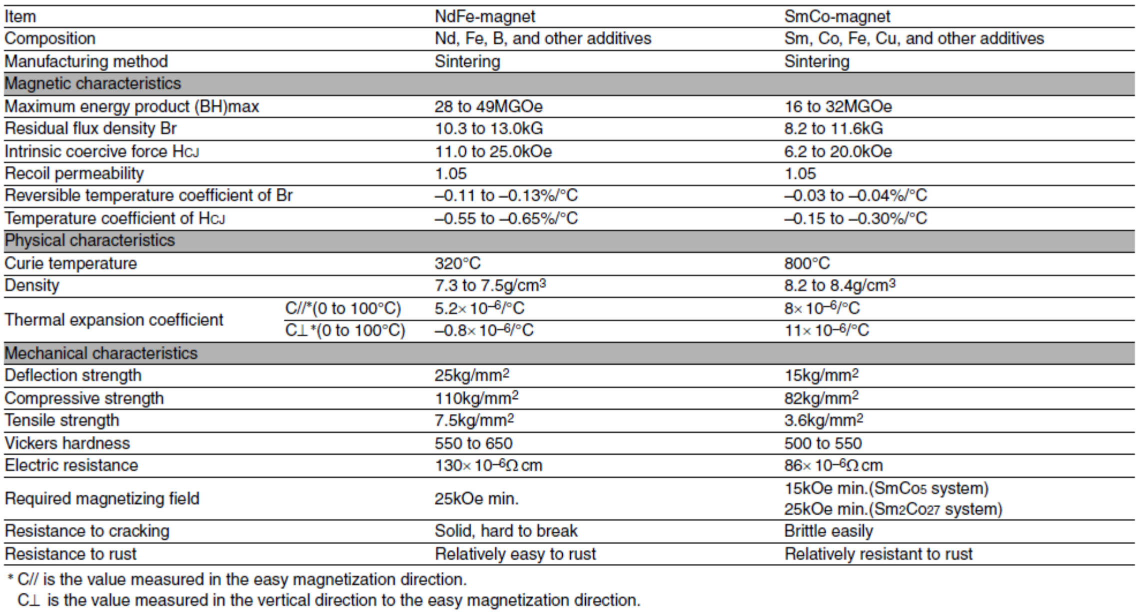
Figure 34 Phase diagram of the Nd2Fe14B system below 920 K [48]

The eutectic reaction between Nd2Fe14B and Nd metal phases plays an important role for enhancing coercivity of the Nd2Fe14B permanent magnets. It seems that the eutectic reaction enables liquid phase sintering, which leads to densification of the alloy without significant grain growth. The optimum temperature for the post sintering heat treatment coincides with the eutectic temperature exactly. The optimum temperature is just below the eutectic temperature and the coercive force decreases rapidly on heating above this temperature. Below the eutectic temperature, phase separation takes place. It is considered therefore that the enhancement of coercive force by post sintering heat treatment results from the removal of defects from the grain boundary area concomitant with the phase separation. [48]

3.3.4. Comparison with same type of hard material: Samarium

When we compare with same type of hard material samarium, the content neodymium is several times higher than that of samarium; iron is, of course, cheaper than cobalt. The magnetic characteristic of neodymium is generally higher than samarium or equal in same cases. But in one point, samarium is very useful. The curie point is higher than neodymium which means that it can preserve its magnetic properties better than neodymium in high working temperatures. In mechanical point of view, neodymium is more durable than samarium. Check figure below: [49]

Table 13 Differences between Nd-Fe-B and SmCo Magnet



Item		NdFe-magnet	SmCo-magnet
Composition		Nd, Fe, B, and other additives	Sm, Co, Fe, Cu, and other additives
Manufacturing method		Sintering	Sintering
Magnetic characteristics			
Maximum energy product (BH)max		28 to 49MGOe	16 to 32MGOe
Residual flux density Br		10.3 to 13.0kG	8.2 to 11.6kG
Intrinsic coercive force H_{cJ}		11.0 to 25.0kOe	6.2 to 20.0kOe
Recoil permeability		1.05	1.05
Reversible temperature coefficient of Br		–0.11 to –0.13%/°C	–0.03 to –0.04%/°C
Temperature coefficient of H_{cJ}		–0.55 to –0.65%/°C	–0.15 to –0.30%/°C
Physical characteristics			
Curie temperature		320°C	800°C
Density		7.3 to 7.5g/cm^3	8.2 to 8.4g/cm^3
Thermal expansion coefficient	C//*(0 to 100°C)	5.2× 10^{-6}/°C	8× 10^{-6}/°C
	C⊥*(0 to 100°C)	–0.8× 10^{-6}/°C	11× 10^{-6}/°C
Mechanical characteristics			
Deflection strength		25kg/mm^2	15kg/mm^2
Compressive strength		110kg/mm^2	82kg/mm^2
Tensile strength		7.5kg/mm^2	3.6kg/mm^2
Vickers hardness		550 to 650	500 to 550
Electric resistance		130× 10^{-6}Ω cm	86× 10^{-6}Ω cm
Required magnetizing field		25kOe min.	15kOe min.($SmCo_5$ system) 25kOe min.(Sm_2Co_{27} system)
Resistance to cracking		Solid, hard to break	Brittle easily
Resistance to rust		Relatively easy to rust	Relatively resistant to rust

* C// is the value measured in the easy magnetization direction.
C⊥ is the value measured in the vertical direction to the easy magnetization direction.

3.3.5. Processing

The permanent magnets are prepared from Nd-Fe-B alloy powder, but since powders are prepared by different methods, their properties, as well as structure, size etc.

Depending on their manufacturing technology, hard magnetic materials may be divided into three basic groups: sintered magnets, cast magnets and magnets bonded with polymer materials called bonded magnets, ferroplasts or dielectromagnets. Depending on their hard magnetic material, magnets are split into the following groups: Al-Ni-Co magnets, ferrite magnets, magnets from cobalt alloys with rare earth group elements, magnets from Nd-Fe-B alloys. Neodymium magnets may be made by sintering, bonding with polymer materials—compacting with the chemically setting or thermosetting resins, bonding with the low-melting glass or metal, injection moulding, hot compacting, upsetting, casting or explosive consolidation. They have various properties and prices depending on technology. Sintered and bonded types of Nd-Fe-B permanent magnets are ones that are used most frequently. [50] [51]

3.3.5.1. Sintered Nd-Fe-B processing

Sintered Nd-Fe-B magnets are manufactured by classic powder metallurgy method. The process is starting together with Vacuum Melting casting and then crushing. Crushing is the process of transferring a force amplified by mechanical advantage through the Nd-Fe-B made of molecules that bond together more strongly and resist deformation. After crushing, the milling process and to obtain align molecules, aligning process is applied. Until sintering process, alloy is powdered and then powder with grain is pressed, after the pressing, sintering, and machining surface treatment are applied respectively to obtain final material. These types of Nd-Fe-B permanent magnets are anisotropic in character and must be magnetized in the same direction as the direction of magnetic field during pressing. Due to high shrinkage during sintering, process magnets must be machined before magnetization. In the figure below, the process is described.

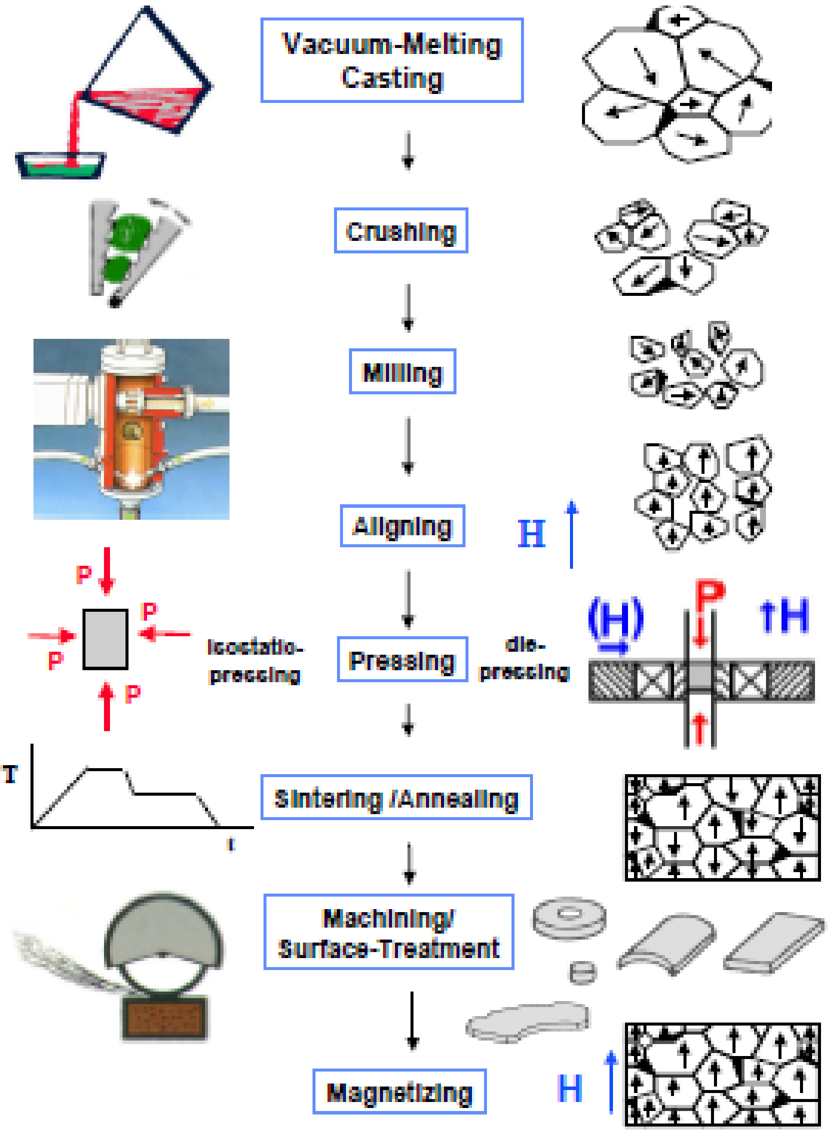


Figure 35 Process of sintered Nd-Fe-B material [43]

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There are limitations on the shapes of magnets produced by sintering, and they often require machining on silicon carbide or diamond grinding wheels to produce the required surface finish and dimensions. [43] [50] [52]

3.3.6. Bonded Nd-Fe-B processing

The technology of preparing bonded magnets, called ferroplasts or dielectromagnets, is simpler than sintering technology, as the process requires lower temperatures, without protective atmosphere. Nd-Fe-B dielectromagnets can be made by compression or injection moulding. Bonded material has several advantages although it has a reduced energy product compared with sintered NdFeB. The flexible bonded NdFeB is a resin bonded isotropic magnet material produced by compression moulding and hot curing to required shape. With this material, small dimensional tolerances are achievable, and the material can be easily machined to finished tolerances. Compared with sintered NdFeB, the flexible bonded material cost is reduced by a factor of two, and it is easily shaped and magnetised for multipole rotor or stator geometries.

Bonded Nd-Fe-B magnets are manufactured mainly in the isotropic version. Isotropic magnets can be magnetized in all direction and multipole. It is very important for many applications, particularly in sensors, such as permanent magnets for position sensors or read relay. The figure below shows examples of multipole magnetization.

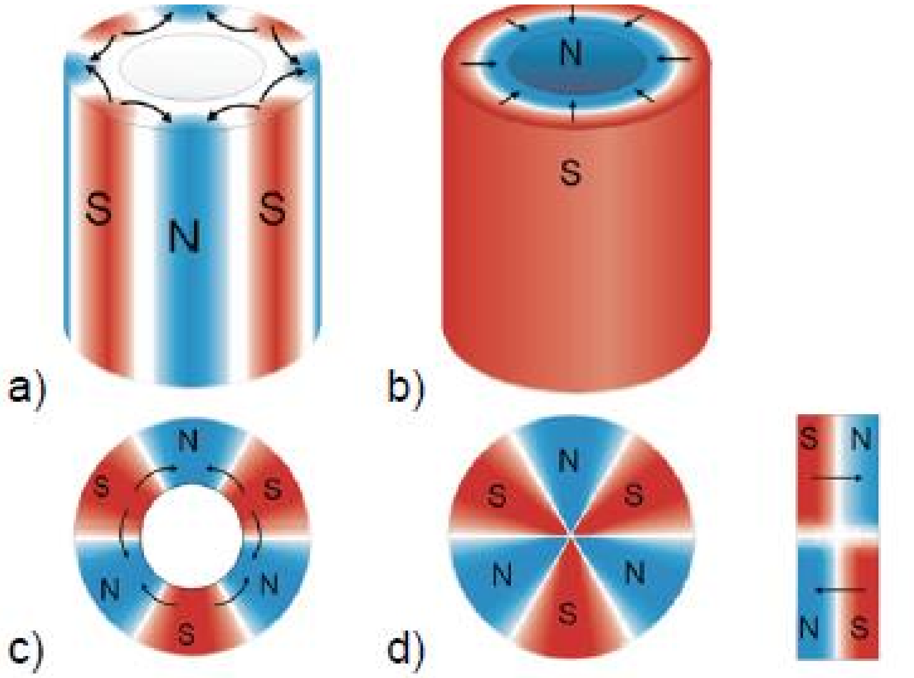
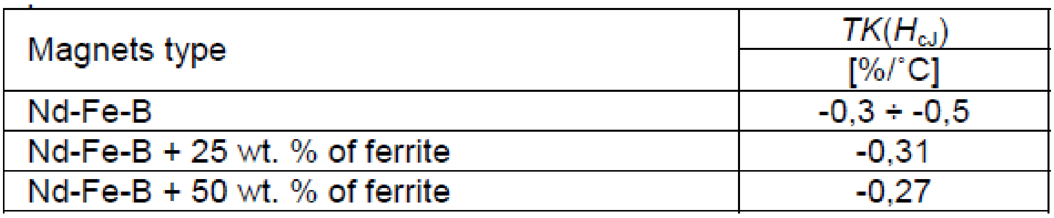


Figure 36 Methods of magnetization (a) multipole on outside circumference, (b) radially oriented, (c) multipole on inside circumference, (d) magnetized axially in segment with alternating poles [50]

Isotropic bonded magnets are also quite widely available. They incorporate flakes of melt-spun Nd-Fe-B in a matrix of resin, plastic, rubber, or metal, but their energy product is only about 20% of that of the sintered magnets, on account of the reduced packing fraction of magnetic material and the absence of crystallite orientation.

The disadvantage of magnets, including dielectromagnets, made from Nd-Fe-B alloys is their thermal properties, mainly the high negative value of temperature coefficient of coercivity. This parameter in many cases makes use of such magnets impossible. One advantage of ferrite magnets is their positive value of temperature coefficient of coercivity. Studies have shown that making dielectromagnets from the mixture of Nd-Fe-B powder and strontium ferrite powder allows us to improve the temperature coefficient of coercivity- Table 14.

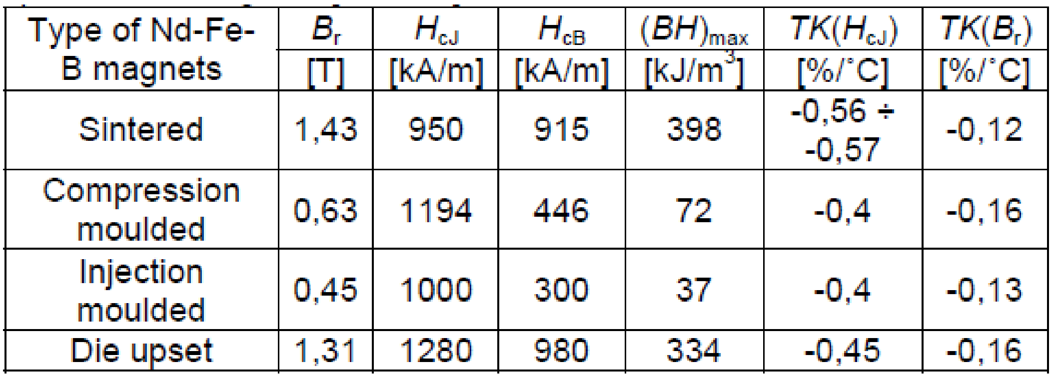
Table 14 Magnetic properties of bonded magnets from mixture of powders



Magnets type	$TK(H_{cJ})$ [%/°C]
Nd-Fe-B	-0,3 ÷ -0,5
Nd-Fe-B + 25 wt. % of ferrite	-0,31
Nd-Fe-B + 50 wt. % of ferrite	-0,27

In general, the table below shows magnetic properties of different type of Nd-Fe-B permanent magnets. [50] [52] [53]

Table 15 Magnetic properties of different types of Nd-Fe-B permanent magnets



Type of Nd-Fe-B magnets	B_r	H_{cJ}	H_{cB}	$(BH)_{max}$	$TK(H_{cJ})$	$TK(B_r)$
	[T]	[kA/m]	[kA/m]	[kJ/m^3]	[%/°C]	[%/°C]
Sintered	1,43	950	915	398	-0,56 ÷ -0,57	-0,12
Compression moulded	0,63	1194	446	72	-0,4	-0,16
Injection moulded	0,45	1000	300	37	-0,4	-0,13
Die upset	1,31	1280	980	334	-0,45	-0,16

3.4. Iron Cobalt Vanadium Fe-Co-V

3.4.1. Set of Properties, where it is used, what purpose and composition

To meet necessary trend, electrical machines require higher power density (> 10 kW/kg), lower power loss, minimised volume, high reliability, and a long service-life. A critical component of the electrical machine is the soft magnetic laminations in the rotor and the stator. Fe-Si alloys are typically used in low-cost, high-volume applications. However, their specific magnetic performance is inferior to Fe-Co alloys, and the latter have been identified as a potential candidate to meet the requirements for the future electrical machines due to its excellent magnetic properties such as the highest saturation flux density (~2.3 T) and Curie temperature (~980 °C), high permeability, low coercivity and low magneto crystalline anisotropy (almost to zero).

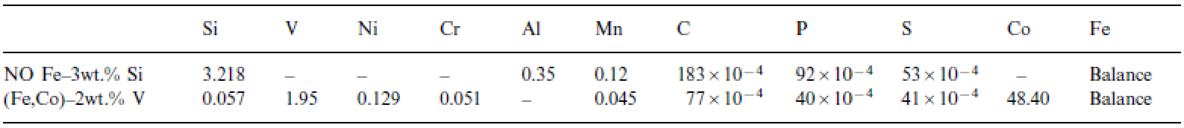
The Iron–Cobalt soft magnetic alloys—based on their high magnetic saturation magnetization *Js* about 20% higher than Si–Fe electrical steel's one—are used when the induced increase of power density is economically favourable, despite the cost of Cobalt. As a result, these alloys (Fe-18%Co-X, Fe-27%Co, Fe-49%Co-2%V in %at) are suitable for on-board applications such as aircraft power generators, transformers and actuators, special electrical machines, or automotive gasoline injectors.

Iron-cobalt based magnetic alloys are known to have the highest saturation magnetization (induction) and high Curie temperature and have a wide range of applications including, but not limited to motor and generator laminations in aerospace, high-performance transformers, magneto strictive transducers, recording media, choke coils, noise filters, and magnetic bearings. Magnetic properties of these alloys can vary within a wide range of magnetically soft to hard behaviour, depending on the applied thermomechanical processing conditions. It is generally accepted that the magnetic properties of Fe–Co–V alloys are affected by the formation of non-magnetic phases in their microstructure during the annealing process.

It is well known that addition of ternary element, typically vanadium, increases the ductility of ternary alloys through the hindering ordering transition during quenching from high temperatures. By addition of V to the binary system, not only mechanical properties, but also magnetic properties are changed and three different types of magnetic materials, based on magnetic hardness, can be gained; namely, soft magnetic Fe-Co alloys containing less than 3% V, semi-hard magnetic alloys known as Remendur (3–5% V) and finally, alloys having the V contents of 6–16%, called Vicalloys which have been developed for hard magnetic applications. In order a more precise classification, hard magnets Vicalloys are also divided into two main groups including Vicalloy I (less than 11% V) and Vicalloy II (higher than 11% V). Such extensive variety in magnetic hardness has been considered to be due to changes in the allotropic austenite (γ) ⇌ ferrite (α) transformation temperature imposed by variation of V content of the alloy as well as formation of non-magnetic Co3V compound. Moreover, it has been reported that the Curie temperature of Fe-Co alloys coincides with the austenite-ferrite transition temperature. In addition to allotropic transformation and precipitation, the ordering transition as well as recrystallization takes place during annealing of ternary Fe-Co-V alloys, so that each phenomenon can affect the magnetic properties.

Non-oriented (NO) Fe–3wt.% Si and (Fe, Co)–2wt.% V alloys are of common use for the conception of electrical motors. Typical compositions are given in the table below. [54] [55] [56]

Table 16 Typical compositions in wt.% of NO Fe–3wt.% Si and (Fe, Co)–2wt.% V alloys, as given by the manufacturers



	Si	V	Ni	Cr	Al	Mn	C	P	S	Co	Fe
NO Fe–3wt.% Si	3.218	–	–	–	0.35	0.12	183×10^{-4}	92×10^{-4}	53×10^{-4}	–	Balance
(Fe,Co)–2wt.% V	0.057	1.95	0.129	0.051	–	0.045	77×10^{-4}	40×10^{-4}	41×10^{-4}	48.40	Balance

3.4.2. Processing

The processing of soft-magnetic Fe49Co49V2 alloys typically includes melting and casting in a vacuum, subsequent hot rolling, followed by cold rolling to obtain thin sheets, and final cutting of the laminates into desired shapes. The powder metallurgy and processing technique and hot isostatic pressing are commonly adopted for manufacturing bulk rotors having the desirable combination of magnetic and mechanical properties. The pre-alloyed powders are often synthesized by inert gas and/or water atomization. The powder and crystallite size (grain size) achievable with atomization technique is limited to a few microns to hundreds of microns. The nanocrystalline powders of Fe49Co49V2 alloys have so far been synthesized by thermal plasma synthesis, mechanical milling, and mechanical alloying. The evolution of morphology and structure during mechanically milling of pre-alloyed Fe49Co49V2 powders have been investigated in the past. The mechanical milling of the pre-alloyed powders results in a reduction in the powder particle size to as low as a few microns and the crystallite size to ~35 nm. While systematic studies on the phase evolution and magnetic properties of nanostructured Fe49Co49V2 powders during mechanical alloying of the constituent elemental powders (Fe, Co, and V) were performed in the past to date, there is not any systematic study in the literature that we are aware of, on the influence on the magnetic properties during mechanical milling of pre-alloyed Fe49Co49V2 powders. [56]

4. CONDUCTORS

4.1. Copper

4.1.1. Set of properties, how can we obtain

As a chemical element, copper is represented by the symbol Cu in the periodic table and has the atomic number 29. As a metal, copper is ductile and malleable and valued for its high thermal and electric conductivity. Copper occurs naturally but its greatest source is in minerals like chalcopyrite and bornite, and you can easily identify it by its reddish-gold colour.

Copper is produced by massive stars and can also be found in our planet's crust. The largest mass of copper found weighed a spectacular 420 tonnes.

4.1.2. Chemical Properties

All common metals and alloys react with a moist atmosphere and corrode. Only in hot/dry (deserts) and cold/dry environments do metals resist corrosion. However, due to the chemical properties of copper, the corrosion process is very slow. The corrosion resistance of copper and copper alloys is based on their ability to form stable compounds that provide some protection from corrosive attack. When exposed to the atmosphere, protective layers of oxides and poorly soluble basic salts form on the surface of copper and copper alloys. Suitable alloying elements can positively influence the formation of these coatings.

The copper element is in the same periodic table group as silver and gold. Therefore, it is relatively inert against chemicals. In most of its compounds it can have the valency (oxidation state) of +I or the valency state +II. The aqueous solutions of copper ions in the oxidation state +II have a blue colour, whereas copper ions in the oxidation state +I are colourless. Copper and copper compounds give a greenish colour to a flame.

4.1.3. Mechanical Properties

The primary mechanical properties of copper—hardness, strength and ductility—determine its condition. The material condition (alternative term: temper) is designated in standards either by the letter H, representing a minimum hardness, or the letter R, representing a minimum tensile strength.

Copper can be supplied in a range of conditions from annealed (soft) to fully hard, which is obtained by cold working.

Annealed copper (H040) has a minimum hardness of 40HV, a minium tensile strength 200 N/mm2(R200) with fully cold worked copper (H110) having a hardness of 110HV minimum and tensile strength of 360 N/mm^2 (R360) minimum.

The ductility of fully cold worked copper is much less than in the annealed condition with a value of 2% elongation.

The strength and hardness of copper can also be increased by alloying, but this results in a decrease in electrical conductivity. The strongest copper alloy of all is produced by alloying with beryllium, followed by an age hardening heat treatment resulting in a tensile strength of up to 1500 N/mm².

4.1.4. Physical Properties

4.1.4.1. Electrical Conductivity

The generation, transmission and use of electricity has transformed the modern world. This has been made possible by copper (of at least 99.9% purity), which has the best electrical conductivity of any common metal – one of the more well-known physical properties of copper. It is available in wrought form as wire, cable, strip and busbars and as castings for such components as electrical switchgear and welding equipment.

4.1.4.2. Thermal Conductivity

Copper is a good conductor of heat (about 30 times better than stainless steel and 1.5 times better than aluminium). This leads to applications where rapid heat transfer is required such as heat exchangers in air conditioning units, vehicle radiators, heat sinks in computers, heat sealing machines and televisions, and as water-cooled furnace components. Good-quality spark plugs have a central copper electrode to enable heat to be removed and prevent overheating. The best quality saucepans are copper bottomed to ensure uniform, rapid heating.

4.1.4.3. Ease of Joining

Copper can be readily joined by brazing, soldering, bolting or adhesives. In industry, this is very useful for plumbing pipework and joining busbars, which are vital elements of power distribution systems. Elsewhere, it is also an important feature for artists crafting sculptures and statues, and for jewellery makers and other artisans working with this beautiful metal. [57]

4.1.5. Production of Copper

The pure copper or high copper alloys are made from copper ores that are obtained from the mines as sulphides, which contain zinc, lead and other sulphur. The ores are crushed and milled until they become a powder. A technique known as flotation separates the metal from the non-metal components of the powder. The next step is a concentrating stage where minerals are concentrated into a slurry that is about 15% copper. The copper is then melted and purified in several stages until it is 99% pure copper. At this point it is cast into anodes. Oxygen remains in the structure as cuprous oxide, Cu2O. Most of the structure is pure copper. The copper metal solidifies from the liquid state by the growth of crystals. The crystals grow in preferred directions and form open, tree like structures called dendrites. The dendritic structure is very typical of cast metals. A lower melting point mixture of pure copper and cupprous oxide, called a eutectic, forms in the open spaces between the dendrites. The eutectic particles are usually dark, globular bodies dispersed in a copper background. The cuprous oxide particles form a network, outlining the dendritic cells. Pores, seen as dark spots in the microstructure, are also present in the as-cast material.

The copper anodes are then refined electrolytically to 99.9% purity. Copper melted under non oxidizing conditions is called oxygen free copper. The most popular form of pure copper is the standard electrical wire grade of copper (C11000) contains 99.95% Cu, 0.03%

O2, and less than 50 ppm metallic impurities. It has a high electrical conductivity, in excess of 100% IACS. In the as cast form it is called electrolytic tough pitch (ETP) copper. The structure of the as-cast material is similar to that described above. When the as-cast ETP copper is hot rolled the eutectic structure is destroyed. The microstructure of the hot rolled copper contains many small grains. Parallel straight lines extending across many of the grains are called annealing twins. They appear after a metal has been mechanically worked at a high temperature, called annealing, and deformed. The interdendritic network of cupprous oxide particles was destroyed by hot rolling. After hot rolling, cupprous oxide particles changed form, and are present as stringers or aligned rows of dark particles. The oxide particles are much larger and fewer in number than in the as cast microstructure. [58]

4.1.6. Applications (Common Areas)

Copper has a huge range of applications. Because this metal conducts heat and electricity extremely well, it is used in electrical equipment, such as wiring, connectors and engines. Copper is also often used in construction (plumbing, for example) and industrial machinery.

It can also be found in boat propellers, saucepan bottoms, water tanks, underfloor heating, car radiators, TV sets, computers, and so much more. The antibacterial properties of copper and its alloys make them incredibly useful for food preparation, plumbing systems, doorknobs and hospitals. Copper sulphate can be found in agriculture as a poison and an algicide in water purification. Copper, brass or bronze can also be used for decorations, such as jewellery, statues and buildings parts (like roofing).

The major applications of copper are electrical wire (60%), roofing and plumbing (20%), and industrial machinery (15%). Copper is used mostly as a pure metal, but when greater hardness is required, it is put into such alloys as brass and bronze (5% of total use).

4.1.6.1. Wire and Cable

Despite competition from other materials, copper remains the preferred electrical conductor in nearly all categories of electrical wiring except overhead electric power transmission where aluminium is often preferred. Copper wire is used in power generation, power transmission, power distribution, telecommunications, electronics circuitry, and countless types of electrical equipment. Electrical wiring is the most important market for the copper industry. This includes structural power wiring, power distribution cable, appliance wire, communications cable, automotive wire and cable, and magnet wire. Roughly half of all copper mined is used for electrical wire and cable conductors. Many electrical devices rely on copper wiring because of its multitude of inherent beneficial properties, such as its high electrical conductivity, tensile strength, ductility, creep (deformation) resistance, corrosion resistance, low thermal expansion, high thermal conductivity, ease of soldering, malleability, and ease of installation.

4.1.6.2. Electric Motors in the car

Copper's superior conductivity enhances the efficiency of electrical motors in the car. This is important because motors and motor-driven systems account for 43%–46% of all global electricity consumption and 69% of all electricity used by industry. Increasing the mass and cross section of copper in a coil increases the efficiency of the motor. Copper motor rotors, a new technology designed for motor applications where energy savings are prime design objectives, are enabling general-purpose induction motors to meet and exceed National Electrical Manufacturers Association (NEMA) premium efficiency standards.

4.1.7. Recycling of Copper

Like aluminium, copper is recyclable without any loss of quality, both from raw state and from manufactured products. In volume, copper is the third most recycled metal after iron and aluminium. The other big importance is using in the car industry. All new improvements are held mostly according to recycling materials in last decades.

The process of recycling copper is roughly the same as is used to extract copper but requires fewer steps. High-purity scrap copper is melted in a furnace and then reduced and cast into billets and ingots; lower-purity scrap is refined by electroplating in a bath of sulfuric acid. [59]

4.1.8. Copper Alloys

One of the interesting facts about copper is that it can, as mentioned above, be alloyed with different types of metals. The following list is by no means comprehensive, but focuses on some of the most used alloys instead:

- **Bronze** – formed when copper alloys with a little tin, the discovery of this new metal led to the beginning of what is known as the Bronze Age.
- **Brass** – when copper alloys with zinc, it creates brass, which is typically yellow in colour and used for a wide range of applications, such as musical instruments.
- **Cupronickel** – this is formed when copper alloys with nickel, which creates a stronger metal used for coins, hardware, marine engineering, and armaments manufacture, amongst other uses.
- **Sterling Silver** – heavily used in jewellery, sterling silver is formed when other metals, such as copper, are added to silver.

Therefore, there are many uses of copper alloys, from everyday items to industry applications such as weapons and car industry. [60]

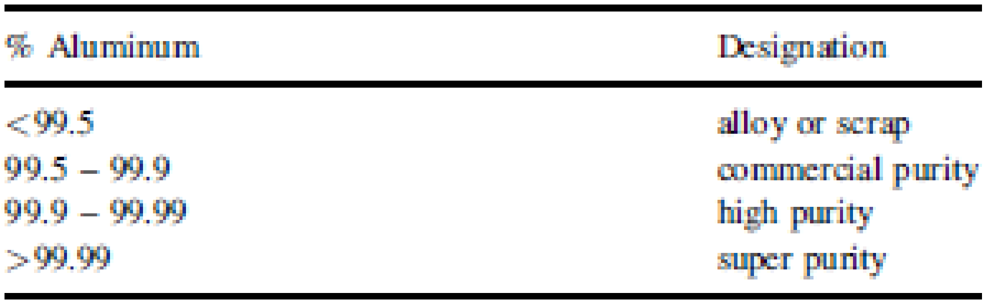
4.2. Aluminium

4.2.1. Set of properties, how can we obtain

Aluminium is the most abundant metallic element in the earth's crust. It is always found combined with other elements. However, elemental aluminium particles have been discovered in lunar soil. Aluminium appears in a wide variety of minerals combined with oxygen, silicon, alkali and alkaline earth metals, and fluorine, and as hydroxides, sulphates, and phosphates. Aluminium has become the predominant nonferrous metal in use, yet it is one of the newest of the common metals. Aluminous minerals are quite stable; large amounts of energy and high temperatures are required to reduce these compounds to metal. This explains why the metal was isolated and produced commercially only in recent times.

Certain physical and chemical properties of aluminium depend primarily on purity. There is no generally accepted nomenclature for the degrees of purity of aluminium. The following classification is suggested:

Table 17 Al classification in terms of purity



% Aluminum	Designation
<99.5	alloy or scrap
99.5 – 99.9	commercial purity
99.9 – 99.99	high purity
>99.99	super purity

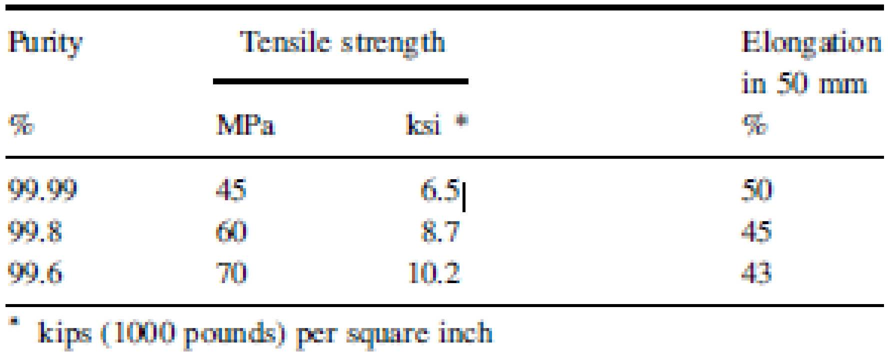
The aluminium produced by the Hall process is of commercial purity. Iron and silicon are the predominant impurities. Aluminium of super purity, produced by the three-layer electrolytic process, first became available in 1920. Methods for preparing aluminium of even higher purity include zone refining, fractional crystallization, and preparation from aluminium alkyls. Electrical resistivity at low temperatures is employed as a measure of purity for high purity and super purity aluminium. Newer methods for analysis of trace impurities, including activation analysis, have improved the sensitivity and scope of analyses for extremely pure materials. Aluminium purer than 99.9999% has been prepared and characterized.

Many applications of aluminium and its alloys are based upon its inherent properties of low density, high electrical and thermal conductivities, high reflectivity, and excellent resistance to corrosion. Pure aluminium is soft and lacks strength, but it can be alloyed with many other elements to increase strength and impart a number of useful properties. Alloys of aluminium are light, strong, and readily formable by many metal-working processes; they can be cast, joined, or machined easily and accept a wide variety of finishes.

4.2.2. Mechanical Properties

Some mechanical properties of aluminium of several purities are given in table below. The data are from different sources and caution should be exercised in any direct comparison. Difficulties occur because of problems in analysis, temper of the specimen, and test methods.

Table 18 mechanical properties of pure Al at room temperature



Purity	Tensile strength		Elongation in 50 mm
%	MPa	ksi *	%
99.99	45	6.5	50
99.8	60	8.7	45
99.6	70	10.2	43

* kips (1000 pounds) per square inch

However, even small amounts of impurities present in commercial aluminium raise the tensile strength and hardness over that of the purest aluminium in the table.

4.2.3. Physical Properties

The physical properties of pure aluminium are summarized in Table 19.

Table 19 The physical properties of pure aluminium

Property	Value
mp	933.5 K
bp	2767 K
Heat of fusion	397 J/g
Heat of vaporization	1.08×10^{-4} J/g
Heat capacity	0.90 J $g^{-1}K^{-1}$
Density (solid)	
theoretical density based on lattice spacing	2699 kg/m^3
polycrystalline material	2697 – 2699 kg/m^3
Density (liquid)	2357 kg/m^3 at 973 K 2304 kg/m^3 at 1173 K
Thermal neutron cross section	$(2.32\pm 0.03)\times 10^{-25}$ cm^2 (0.232±0.003 barn)
Lattice constant (length of unit cube)	4.0496×10^{-10} m at 298 K
Coefficient of expansion	23×10^{-6}/K at 293 K
Thermal conductivity	2.37 W $cm^{-1}K^{-1}$ at 298 K
Volume resistivity	2.655×10^{-8} Ω m
Magnetic susceptibility	16×10^{-3} mm^{-3} mol^{-1} at 298 K
Surface tension	8.68×10^{-3} N/cm at the *mp*
Viscosity	0.0012 Pa · s at the *mp*

4.2.4. Atomic Structure of Al

Aluminium has an atomic number of 13 and atomic mass of 26.98154 based on C. The only abundant isotope, Al, is stable and consists of 14 neutrons and 13 protons. Except for a single isotope, Al, which has a half-life of 10_6 years, all isotopes have half-lives of less than 8 s and are of negligible abundance.

4.2.5. Thermal Conductivity

Above 100 K the thermal conductivity of well-annealed 99.99% aluminium is relatively insensitive to the impurity level. Below 100 K thermal conductivity becomes highly sensitive to the level of impurities. Values for thermal conductivity are given in the table below.

4.2.6. Electrical Resistivity

The application of aluminium as an electrical conductor depends upon the low electrical resistivity of unalloyed aluminium. The electrical conductivity of pure aluminium at room temperature is 64.94%of that specified for copper in the International Annealed Copper Standard (IACS), but on an equal-weight basis, aluminium exceeds the electrical conductivity of copper. At temperatures below 50 K, the electrical resistivity of aluminium is less than that of copper and silver of very high purity. Aluminium becomes superconducting below 1.2 K.

The resistivity of aluminium below 100 K is highly sensitive to impurities. The residual resistivity ratio (RRR), or the ratio of electrical resistivity at room temperature to that at 4.2 K (boiling point of helium), is sometimes used as a measure of purity. Resistivity ratios of more than $3x10_4$ have been reported for 99.999% aluminium.

4.2.7. Chemical Properties

Aluminium is one of the most reactive of the common commercial metals, it is remarkably stable in many oxidizing environments. It owes its stability to the continuous film of aluminium oxide that rapidly grows on a nascent aluminium surface exposed to oxygen, water, or other oxidants. The molecular volume of the oxide is about 1.3 times greater than that of the aluminium consumed in the oxidation reaction.

Aluminium can react at high temperature. Molten aluminium reduces many compounds containing oxygen. These reactions are used in the manufacture of certain metals and alloys by the thermite reaction. [61]

4.2.8. Production

The production of aluminium starts with the extraction of bauxite rock from the ground. **Bauxite** is a sedimentary rock with a relatively high aluminium content. It is the world's main source of aluminium and gallium. Bauxite consists mostly of the aluminium minerals gibbsite ($Al(OH)_3$), boehmite (γ-$AlO(OH)$) and diaspore (α-$AlO(OH)$), mixed with the two iron oxides goethite ($FeO(OH)$) and haematite (Fe_2O_3), the aluminium clay mineral kaolinite ($Al_2Si_2O_5(OH)_4$) and small amounts of anatase (TiO_2) and ilmenite ($FeTiO_3$ or $FeO.TiO_2$).The bauxite is processed and transformed using the Bayer process into alumina, which is then processed using the Hall–Héroult process, resulting in the final aluminium metal.

Aluminium production is highly energy-consuming, and so the producers tend to locate smelters in places where electric power is both plentiful and inexpensive.

4.2.8.1. Bayer process

Bauxite is converted to alumina by the Bayer process. Bauxite is blended for uniform composition and then is ground. The resulting slurry is mixed with a hot solution of sodium hydroxide; the mixture is then treated in a digester vessel at a pressure well above atmospheric, dissolving the aluminium hydroxide in bauxite while converting impurities into relatively insoluble compounds:

$$\text{Al (OH)}_3 + \text{Na}^+ + \text{OH}^- \rightarrow \text{Na}^+ + [\text{Al (OH)}_4]^-$$

After this reaction, the slurry is at a temperature above its atmospheric boiling point. It is cooled by removing steam as pressure is reduced. The bauxite residue is separated from the solution and discarded. The solution, free of solids, is seeded with small crystals of aluminium hydroxide; this causes decomposition of the $[\text{Al (OH)}_4]^-$ ions to aluminium hydroxide. After about half of aluminium has precipitated, the mixture is sent to classifiers. Small crystals of aluminium hydroxide are collected to serve as seeding agents; coarse particles are converted to alumina by heating; the excess solution is removed by evaporation, (if needed) purified, and recycled.

4.2.8.2. Hall-Heroult Process

The conversion of alumina to aluminium metal is achieved by the Hall–Héroult process. In this energy-intensive process, a solution of alumina in a molten (950 and 980 °C (1,740 and 1,800 °F)) mixture of cryolite (Na_3AlF_6) with calcium fluoride is electrolyzed to produce metallic aluminium. The liquid aluminium metal sinks to the bottom of the solution and is tapped off, and usually cast into large blocks called aluminium billets for further processing.

The Hall–Heroult process produces aluminium with a purity of above 99%. Further purification can be done by the Hoopes process. This process involves the electrolysis of molten aluminium with a sodium, barium, and aluminium fluoride electrolyte. The resulting aluminium has a purity of 99.99%.

4.2.9. Applications

Aluminium is almost always alloyed, which markedly improves its mechanical properties, especially when tempered. For example, the common aluminium foils and beverage cans are alloys of 92% to 99% aluminium. The main alloying agents are copper, zinc, magnesium, manganese, and silicon (e.g., duralumin) with the levels of other metals in a few percent by weight. Aluminium, both wrought and cast, has been alloyed with: manganese, silicon, magnesium, copper and zinc amongst others. [62]

4.2.10. Automotive Applications

In recent years Al has been of increasing interest for automotive applications due to general need in weight saving for further reduction in fuel consumption. Especially sheet applications for new light weight structural parts and body in white construction are gaining interest and major efforts have been given by all major producers of semi-finished products of Al Alloys to meet the main requirements are:

- Sufficient strength for structural stability and durability
- Good formability for stretching, bending and deep drawing operations
- Joining, like welding
- High corrosion resistance
- Recyclability and low material and fabricating cost

For structural parts and for body in white application, the two main alloy systems used are Al-Mg and Al-Mg-Si which are well established due to their good combination of the required properties.

4.2.11. Microstructure Evolution During Sheet Production of Al-Alloys

A schematic plot of the processing route for conventional production of Al sheet alloys by DC-ingot casting, hot and cold rolling and final annealing treatment is shown in Figure 38. In the different stages the material is transformed from the as cast structure into a fine-grained recrystallized structure by hot and cold rolling and final soft annealing or solution heat treatment in continuous annealing surface. Figure 39 shows the corresponding microstructures and textures typical for most Al alloys. [63]

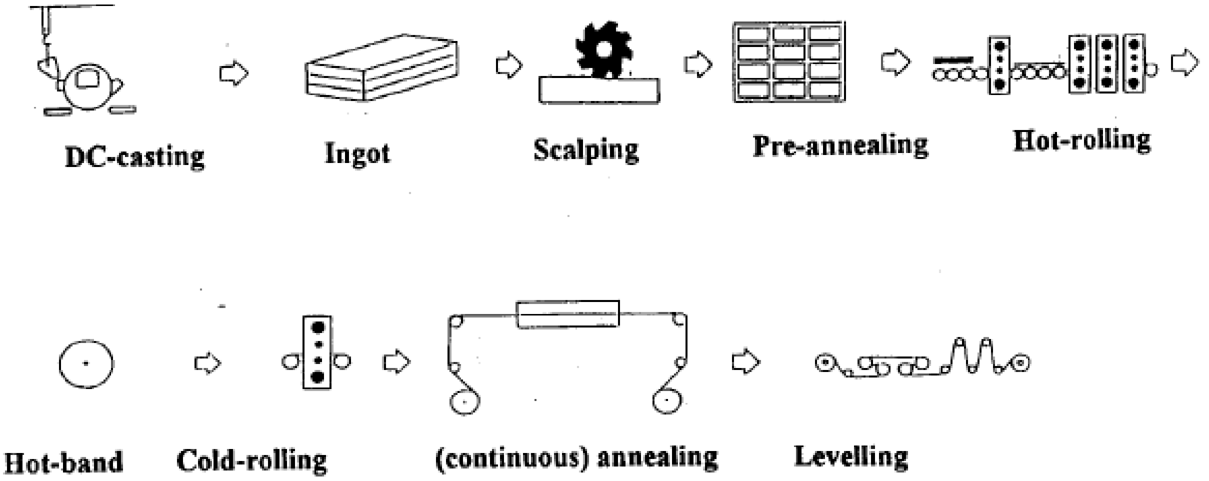


Figure 37 Schematic processing route for Al sheet for automotive applications [63]

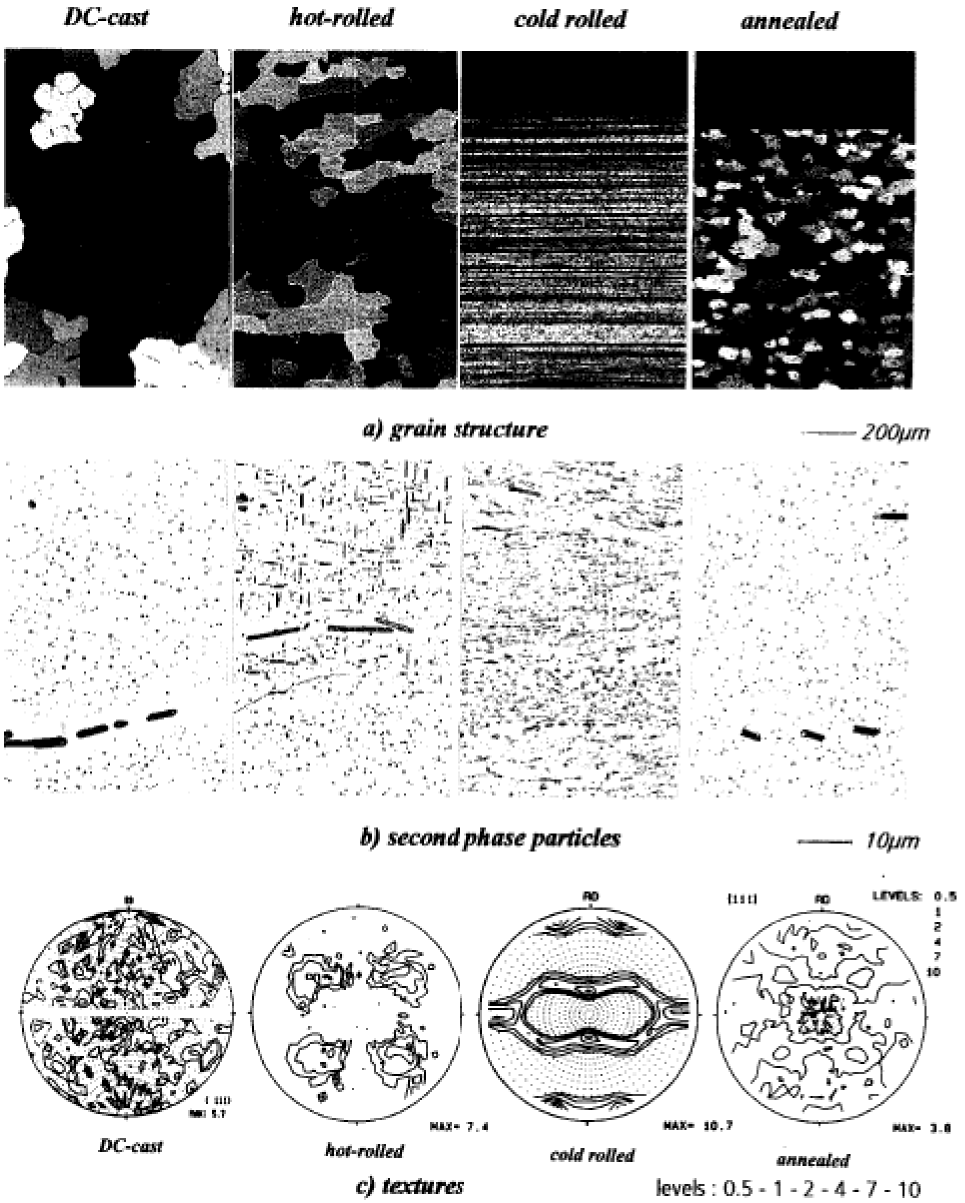
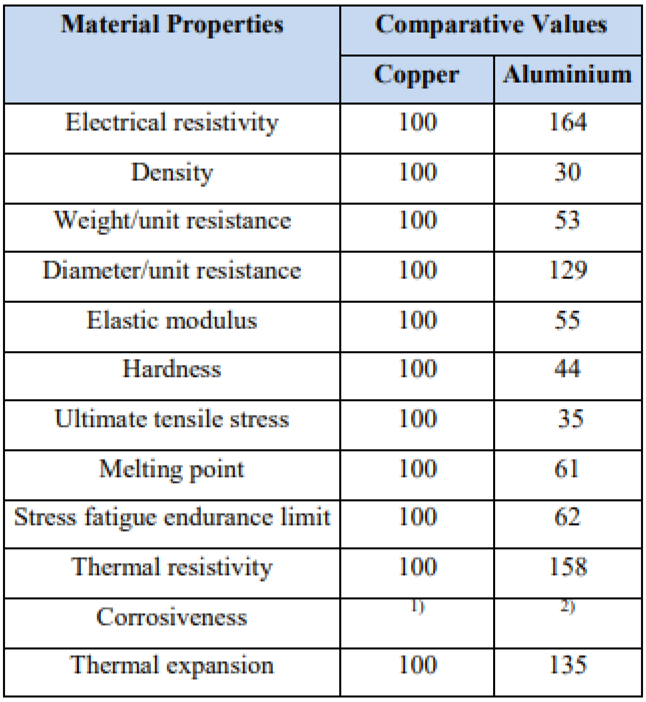


Figure 38 Typical microstructures in different processing stages of Al alloy sheet [63]

4.2.12. Copper vs Aluminium Conductors Used in the Vehicles

Copper for its high electricity conductivity, is the most frequently used metal in car wiring. In recent years, with increasing demand for CO2 emission reduction, demand for weight reduction has increased. Meanwhile, the price of copper is soaring. Automakers continue to look for an alternative material to reduce weight and cost. Aluminium is the metal that is replacing copper. Aluminium is lighter and far more affordable. But on the other hand, Al has lower electric conductivity and less corrosion resistance.

Table 20 Copper vs Aluminium comparative material properties in the pure state



Material Properties	Comparative Values	
	Copper	**Aluminium**
Electrical resistivity	100	164
Density	100	30
Weight/unit resistance	100	53
Diameter/unit resistance	100	129
Elastic modulus	100	55
Hardness	100	44
Ultimate tensile stress	100	35
Melting point	100	61
Stress fatigue endurance limit	100	62
Thermal resistivity	100	158
Corrosiveness	1)	2)
Thermal expansion	100	135

In addition to a lower price tag, aluminium wiring is somewhat easier to work with a copper wiring. Copper wiring is stronger, so it’s less likely to break. Aluminium wiring, however, is more flexible, making it easy to work with in small spaces. Hopefully, this gives you a better understanding of how copper wiring and aluminium wiring differs from each other. [64] [65]

5. CONCLUSION

The Electrical Machines have very critical point in the vehicle electric system to obtain proper power output and efficiency. In the light of developing technologies, there are different kind of electrical machines which use in the cars. The most common ones were explained as Lundell Alternator, Induction Machine, Permanent Magnet Synchronous Machine, Axial Flux Permanent Magnet Synchronous Machine, Switched Reluctance Machine and Synchronous Reluctance Machine. The all of them have different characteristics which are affecting the car performance.

Lundell is the predominant machine used as a generator in conventional vehicles. It can reach high operational speeds. The efficiency and power output are limited in the Lundell Alternators, and this is the major drawbacks of the Lundell Machine. It is characterized by low efficiency due to important mechanical, copper and magnetic losses when you compared with other electrical machines. Induction Machine is another type of electrical machine which used in the vehicles. They have robust structure and mature manufacturing technology. The power density is lower than other type of electrical machines and the constant power region is not as wide as permanent magnet machines. In cost point of view, it has lower cost than permanent magnet machines.

On the other hand, there are some kind of more technological electrical machines in the vehicles. One of them is the Permanent Magnet Synchronous Machine. The magnetic core of the Permanent Magnet Synchronous Machine (interior) for both rotor and stator is hard magnetic material. Desirable properties high permeability and saturation point low losses and for the rotor, sufficient mechanical strength to support required rotational speed. Used material generally is Fe-Si (Silicon-iron) alloy. Also, Fe-Co-V alloy (vanadium-cobalt iron) is another alternative. Permanent magnets specifications are high energy density, magnetic coercivity, remnant magnetic flux density and working temperature. Neodymium-iron-boron Nd-Fe-B is the most preferred material in electrical machine design due to its higher values of energy density and remnant magnetic flux density than other alternatives. In similar to this machine, also the AFPMSM electrical machines which can be seen in electric vehicle powertrains and in-wheel motors. The magnetic core material is commonly Nd-Fe-B. As it in the PMSM, the main parts are the rotor, stator, and windings. AFPMSM is widely used in the automotive electric industry due to its high power and torque density, minimize torque ripple and also its pancake structure.

Other last two electrical machines are SRM and SYR in the cars. The SRM is a cost-efficient motor without need of expensive rare-earth materials. There is no permanent magnet or other external excitation in a SRM. On the other hand, the SYR relies on the absence of rotor copper losses that permits continuous torque that can be higher than an IM of the same size. The rotor is potentially less expensive than both PM and IM due to cancelling cage, winding and magnets from its structure.

The common materials which used in the electrical machines are defined according to the academic research of thesis. These materials are Pure Iron, Iron-Silicon, Neodymium-Iron-Boron and Iron-Cobalt-Vanadium.

In the base of materials, the electrical steels have desirable requirements to help for choosing the right material. These are high permeability, low magnetostriction, high electrical resistivity and decreased hysteresis losses. The electrical steels can be classified as soft magnetic materials according to their properties. In addition to these materials, the rare earth materials are used in the industry. The use of these materials has resulted in significant improvements in performance, commercial, space and military applications.

Pure iron has excellent magnetic properties: large saturation polarization, low coercivity, and high permeability. But the main problem is that such performance is displayed only by pure iron: even small quantities of impurities cause significant deterioration of magnetic properties.

In the electrical motors in addition to Pure Iron, generally the alloys are used. The Fe-Si are currently most used material in the realization of electric motors, because they offer a relatively low cost and excellent magnetic properties (low loss, high permeability, high saturation induction, low coercive field). It is known also has excellent soft magnetic properties. Among various metal cores, Fe-Si alloy powders have been considered to be one of the most suitable candidates due to low price and excellent soft magnetic properties. Silicon steels containing about 3.0 wt% Si are widely used as core materials in transformers, magnetic amplifiers and many other electronic devices.

The permanent magnets play an important role in the contemporary technology. Thanks to their properties, the electrical machines can give more efficiency and performance. In this field the Nd-Fe-B is playing very important role in the electrical machines. They are used in the magnetic core of them. But the biggest disadvantage is their costs. Nevertheless, when the magnetic properties are considered, the application area of them is getting increase year by year not in the electrical machines but also in the car industry.

The last material which described in this thesis is Fe-Co-V in the electrical machines. Firstly, the Iron-Cobalt soft magnetic alloys based on high magnetic saturation is higher than Fe-Si electrical steel and they are used when the induced increase of power density is economically favourable, despite the cost of Cobalt. Generally, they are suitable for generators, transformers and actuators. Mostly, the material is used in the automotive gasoline injectors. By addition of V to the binary system, not only mechanical properties, but also magnetic properties are changed and named differently.

In terms of conductors in the electrical machines, the most preferable ones are copper and Aluminium. Copper for its high electricity conductivity, is the most frequently used metal in car wiring. In recent years, with increasing demand for CO2 emission reduction, demand for weight reduction has increased. Meanwhile, the price of copper is soaring. Automakers continue to look for an alternative material to reduce weight and cost. Aluminium is the metal that is replacing copper. Aluminium is lighter and far more affordable. But on the other hand, Al has lower electric conductivity and less corrosion resistance.

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