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# Selection and design of soft magnetic materials for transformer core applications

**Deepika Sharma**

*School of Physical Sciences, Lovely Professional University, Phagwara, Punjab, India*

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**ABSTRACT**

*Soft and hard magnetic components are produced from a large number of ferrous-based materials processed through wrought as well as through powder metallurgy route. However, iron-phosphorous alloy system for the production of magnetic materials is not known in wrought processing route in spite of the fact that phosphorous as an alloying element has all the favourable characteristics to enhance magnetic properties of iron. This is because of the fact that in wrought route it is not possible to bring phosphorous in homogeneous solid solution with iron due to its segregation tendency during solidification of the melt. This renders the alloy completely useless not only from magnetic point of view but also from mechanical properties as well. Powder metallurgical (P/M) processing, on the other hand, due to predominantly its solid state processing approach, has been very successful in exploiting potential of Fe-P alloy systems for magnetic as well as mechanical applications. A large number of products such as magnetic cores of contactors and relays for DC voltage, cores of magnetic brakes of various time relays and electricity meters have come out of this system through P/M processing. Techniques are developed to reduce eddy current losses so as to use the material in AC applications.*

**Key words:** Powder Metallurgy, Transformer Cores, Forging, Soft Magnetic Materials

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## INTRODUCTION

Soft magnetic materials being easily magnetized or demagnetized and whose hysteresis loops are narrow, play a fundamental role in designing electrical and electronic machines, equipments and devices. Basically it is the material and secondly the design, which control the performance (smooth running without any humming sound) and efficiency (minimum losses in energy conversion) of a device. In turn the material development, improving performance of electrical/electronic devices will add to the comforts of a common man that leads to the developments of society to modernization.

Soft magnetic materials exhibit magnetic properties only when they are subjected to a magnetizing force such as the magnetic field created when current is passed through the wire surrounding a soft magnetic core. Soft ferromagnetic materials are generally associated with electrical (DC as well as AC) circuits where they are used to amplify the flux generated by the electric currents. It is the flux multiplying power of magnetically soft magnetic materials, which fits them for their job in machines and devices. The materials with high duty flux multiplier are most suited for making cores of transformers, generators, and motors. These machines are usually large and heavy, so that the cost per unit weight is important; these cores are made of electrical steels, which is the cheapest available magnetic material at present. The materials (such as Fe-Ni alloys) with light duty flux multiplier are used for making cores of small, special purpose transformers, inductors, etc.; being used in communication systems, where cost consideration is usually secondary to some particular magnetic requirements such as quick response to the current in the device. The materials (such as soft ferrites and Fe-Ni alloys) with square hysteresis loop are used in computers and in magnetic amplifiers and other ‘saturable-core’ devices. The microwave system components comprise soft ferrite and garnets. Thus, soft magnetic materials play a key role in power distribution, and make possible the conversion between electrical and mechanical energy, underlie microwave communication, and provide both the transducers and the active storage material for data storage in information systems. The qualities of magnetic materials are continuously being improved, and many new applications are possible. In fact, magnetic materials seem to offer an infinite variety of applications, when one application is displaced another arises.

Business Communications Company's reports viz. GB-149B and BG-192 [1] on technical/economic study review the technology of soft magnetic materials, new developments in materials and processing techniques, the types of soft magnetic materials, their properties and applications, current and anticipated demand on the basis of an extensive US market analysis. The information in these reports are based on the interviews with almost all producers of soft magnetic materials in US, distributors, and major users of soft magnetic materials and the data obtained from industry associations such as Magnetic Materials Producers Association (MMPA); American Society of Materials (ASM); trade publications; technical journals; government statistics, such as from the U.S. Dept. of Commerce (Bureau of Census); and U.S. Patent Database. BCC's report GB-268 [2] reviews the magnetic materials market in China and its position in the world market; China has presently surpassed Japan in terms of quantity and is ambitious to have a strong hold in international market in the production of magnetic materials during tenth five year plan (2001-2005). The consumption of soft magnetic materials particularly in electrical machines, electrical devices and equipments is on a large scale and is measured in terms of quantity as well as in terms of money being spent. As an example, the annual sales of so called electrical steel, used in electromotors and similar devices, reach the millions of tons and their market values are in hundreds of millions dollars [3]. Electrical steel, which covers about 60% of the total soft magnetic materials, is used to multiply the magnetic flux in the cores of electromagnetic coils. These materials are therefore widely incorporated in many electrical machines in daily use. Among their applications are cores of transformers, electromotors, generators, or electromagnets. In order to make these devices most energy efficient and economical, one needs to find magnetic materials, which have the highest possible, saturation magnetization and permeability (at the lowest possible price). Furthermore, magnetic core materials should be capable of being easily magnetized or demagnetized. In other words, the hysteresis loss or the area within the hysteresis loop (or the coercive force, $H_c$) should be as small as possible and the amount of core losses should also be low. The energy losses which are encountered in electromotors (efficiency between 50% and 90%) or transformers (efficiency 95-99.5%) are estimated to be, in the United States, as high as $3x10^{10}$ kWh per year, which is equivalent to the consumption by about 3 million households, and which wastes about $\$2x10^9$ per year [3]. If by means of improved design of the magnetic cores, the energy losses would be reduced by only 5%, one could save about $\$10^8$ per year and several electric power stations. Thus, there is a clear incentive for improving the properties of the existing magnetic material and developing new. The main competition revolves around electrical steel and cold-rolled steel laminations being produced by alloying through melting route.

Powder metallurgical (P/M) route of manufacturing has its inherent advantages such as the utilization of the material to a greater extent, ability to get the product in net shape without subsequent machining or incorporating any other additional forming operation. Further, it makes possible of alloying of an element in a system to a higher amount if so desired, which is otherwise not possible through melting route. As an example, phosphorous exceeding above 0.05% in wrought steels renders brittleness, however, tough homogeneous solid solution forms up to 1% P in iron when it is diffused during sintering of compacted admix iron-phosphorous powders. At the same time, P/M processing makes it possible to tailor the magnetic properties of a part to suit a specific application by effectively controlling the powder characteristics, material's chemistry and processing parameters. Thus P/M processing offers the material and product designer a wide flexible range and a greater scope for material's development.

The sintered parts mostly as solid cores made of pure iron, are now well established in the market for soft magnetic applications. These components at high sintered density possess high saturation magnetization, however exhibit limited strength and low resistivity. Therefore, the use of pure iron powder for P/M soft magnetic components is limited only for DC applications and where not much strength is required. Further the soft magnetic components in single solid piece form are made from choosing among Fe-Si, Fe-P, Fe-Ni and ferritic stainless steel alloy powders for specific applications.

**LITERATURE REVIEW**

The present review predominantly deals with the literature on ferrous soft magnetic materials produced from powders, using compacting and sintering. Soft magnetic materials are used in the manufacture of electrical machines, transformers and many kinds of electrical equipments, instruments and devices. Electrical steels made of pure iron powders, iron-silicon and iron-phosphorous premixed alloy powders that are produced through P/M route have improved magnetic characteristics than wrought electrical steels which are commercially available. Further, the P/M soft magnetic components are also being produced from Ni-Fe alloy powders and ferritic stainless steels for specific use. Solid core materials are normally used for parts of magnetic circuits carrying steady flux such as cores of DC electromagnets, relays and fields frames of DC machines. The basic requirement for steady magnetic fields is high permeability, particularly at high values of flux densities. For majority of uses it is also desirable that hysteresis loss be as low as possible.

Pure iron (or iron with low content of carbon and other impurities) is widely used in many kinds of electrical equipments and instruments such as in making cores and pole shoes for electromagnets. Pure iron cores are susceptible to ageing where magnetic properties deteriorate in service with time, which in turn causes cumulative overheating and subsequent breakdown. Low carbon electrical steels have large eddy curry losses (Because of low resistivity) if they are operated at high flux density in AC fields. This limits their use to fields carrying steady flux or weak AC field. Addition of silicon in iron virtually eliminates ageing problem, further, it reduces the hysteresis loss, and by augmenting the resistivity it decreases eddy-current losses. The greater the silicon content, the better is the steel from the viewpoint of hysteresis and eddy current losses. Non-oriented electrical steel sheets are used for the magnetic circuit of electrical machines and cores of the transformers. Presently laminations used in electrical machines and in transformers working at or near supply frequencies are made of silicon steel in which the contents of silicon varies from 0.3% to 4.5%. Unfortunately the addition of silicon lowers the saturation induction and as well as ductility. Therefore, above 5% silicon content, the resulting Fe-Si alloy steel (or also known as silicon iron-as it has very low carbon) is brittle. Where core loss is unimportant (as in low frequency DC machines) or where the magnetic current is kept low (as in induction motors) a low silicon iron is employed. On the other hand, in large machines, particularly in turbo-alternators where the highest possible efficiency is desired a low-loss (as Fe-2 to 4%Si alloy) steel is employed. Cold rolled grain oriented silicon steel sheet (popularly known as c.r.o.s.) possesses strong directional magnetic properties (the rolling direction being the direction of highest permeability and lowest hysteresis loss). This material is suitable for use in transformers and also in large turbo-alternators where the axis of core can be made to correspond with rolling direction of the sheet and therefore full use is made of high permeability and low loss direction of the sheet. The cold rolled grain oriented steel has about 3%Si. Further, silicon steel sheets possessing higher silicon content (4-5% silicon) called “transformer grade steels” are mainly used in distribution transformers here the criteria for the selection is to have low losses and not much importance is attached to the magnetizing current. This steel is called “high resistance steel (h.r.s.)” on account of its high resistivity and consequently low eddy current loss. In rotating electrical machines it is desirable to work the iron parts at higher values of flux density in order to achieve a higher output to weight ratio. The magnetic material, therefore, should have a high saturation flux density and hence the presence of silicon is a disadvantageous. Therefore in these machines steels with low silicon contents are used and these steels are termed as “dynamo grade steel”.

Fe-Ni alloys possess high initial and maximum permeability so that high flux density is obtained even in weak magnetic fields. Further high nickel-iron alloy (such as 78 permalloy) has high resistivity too which makes it suitable for magnetic amplifiers, weak current transformers, DC relays, communication and control equipment. Low nickel-iron alloy containing nickel from 38 to 50% along with about 3%Si or 3% Mo has lower permeability than high nickel variety, however it has higher resistivity and is used in making high frequency induction coils, chokes and communication equipment. The material used for current transformer requires constant permeability, which is independent of field strength and these are made of perminvar (usually it contains 45%Ni-30%Fe-25%Co). It has zero hysteresis loss at low field strength. A cheaper alloy, know as 7-70 permivar containing 7%Co-70%Ni-23%Fe is in much use than the original one. To provide a strong magnetic field in the air gap of apparatus such as electromagnet, oscillographs, microphones it is necessary to have a material capable of setting up a flux density much greater than that obtained with electrical steel. An alloy meeting above requirement is permendur (49% Co-49%Fe-2%V). Soft Magnetic materials for automotive applications require superior performance, conformance to tight tolerances, a zero defect rate, warranted environmental safety and minimal cost [4]. Available P/M materials for magnetic applications include pure iron, iron-phosphorus alloys, iron-silicon alloys, iron-nickel alloys and stainless steels. Table 1 summarizes these materials according to relative raw material cost [5], typical part densities, and the resulting magnetic performance [6]. Table 2 summarizes the material’s choice on the basis of selection criteria for some of the components made through P/M route for soft magnetic applications.

**Table 1: Typical properties of P/M Magnetic Materials [5,6]**

| Alloy System | Typical Density ($g/cm^3$) | Approx. Relative Cost [19] | Max. Permeability $\mu_{max}$ | Coercivity $H_c$ (Oe) | $B_{max}$ @ 15 Oe (kG) | Resistivity,ρ (μ Ω cm) |
|---|---|---|---|---|---|---|
| Fe | 6.8-7.2 | 1 | 1800-3500 | 1.5-2.5 | 10-13 | 10 |
| Fe-P | 6.8-7.4 | 1.2 | 2500-6000 | 1.2-2.0 | 10-14 | 30 |
| Fe-Si | 6.8-7.3 | 1.4 | 2000-6000 | 0.8-1.2 | 9-13 | 60 |
| 400 Series Stainless Steel | 6.7-7.2 | 3.5 | 1400-2100 | 1.5-2.0 | 9-11 | 50 |
| 50 Ni/ 50Fe | 7.2-7.6 | 10 | 5000-15000 | 0.2-0.5 | 9-14 | 45 |

**Table 2: Selection criteria and P/M materials for soft magnetic applications [7, 8]**

| Application in | Selection criteria | Material choice |
|---|---|---|
| Motor frame | High saturation induction and high density alloys | Pure iron, Fe-P sintered materials |
| Pole pieces | High saturation induction, high density and high permeability alloys | Fe-P, Fe-Si sintered materials |
| Relays and actuators | Quick response to applied current, high permeability and low coercivity | Fe-P, Fe-Si, 50 Ni/50Fe sintered alloys |
| Anti-lock Breaking System- toner rings | Good corrosion resistance and high permeability | 400 SS, Fe-treated with corrosion resistant coatings, Fe-P sintered alloys |
| Other sensors | Good corrosion resistance and high permeability | 400 SS, Fe-treated with corrosion resistant coatings, Fe-P sintered alloys |
| Automatic ignition coil | High resistivity with moderate magnetic performance | Plastic coated iron powder compacts |
| Electromechanical component of Interactive Torque Management (ITM) system for vehicle to have a greater vehicle control during acceleration and braking | Good magnetic performance to quickly activate the torque transfer system, good wear resistance and a high tensile strength | FL-4400 with an increased P content up to 0.8%; Mo when added to steels has a strong attraction with P, minimizes the risk of embrittlement. |

The desired magnetic properties in P/M soft magnetic materials may be obtained by selecting appropriate alloy chemistry and optimizing the processing parameters. The requirement of high density is a predominant factor for improving the performance of powder metallurgy components employed in soft magnetic applications. Traditionally, density is increased by raising compaction pressure, elevating sintering temperature, adding elements for activating sintering process; using double press/double sinter (DPDS), copper infiltration and powder forging methods. It has been stated that hot forging technique for making heavy duty brake pads offer a better opportunity for pore free material with better bonding between various metallic and non metallic constituents [9]. The material so produced has been characterized for specific wear, temperature rise during engagement, coefficient of friction, hardness and density [9].

The techniques summarized below mainly comprise of improving the powder characteristics of magnetic materials in order to support conventional compacting and sintering process to yield high density values and hence soft magnetic properties. However, there seems to be no attempt in producing soft magnetic materials with relaxed powder characteristics and alternative processing. Table 3 lists the benefits and weaknesses associated with these processes.

The pressure sintering is becoming popular as a means of achieving near theoretical density in powder preforms. In this case, pressure and temperature are applied together so that compaction and sintering take place concomitantly. The results of computer simulation on pressure sintering using finite element analysis for isostatic as well as uniaxial pressure conditions has shown that the densification rate depends on many variables such as creep parameters (grain size, diffusion coefficient and mechanism of deformation etc.), process variables (pressure, temperature, and particle size, shape and distribution), geometric variables (porosity and aspect ratio etc.), and boundary variables (mode of pressing and die wall friction) [10].

**Table 3: Benefits and weakness of various P/M processes [11]**

| Process | Benefits | Weakness |
|---|---|---|
| Conventional compaction | Inexpensive | Limited density capability |
| | Wide range of part shapes possible | |
| Double press/Double sinter | High density | Expensive |
| | | Limited part shapes |
| | | Double processing |
| Copper Infiltration | Improved performance | Expensive |
| | | Double processing |
| Powder Forging | Near to full density | Very expensive |
| | | Complicated processing |

Further, new methods are developed by modifying the existing ones for the production of P/M parts to improve performance, efficiency and life of the components and to make them suitable in a wider range of applications. Most of these methods are of commercial importance and many of them have been patented. Coating (substantially free from organic materials), consisting of 2 to 3 parts of an oxide and one part of chromate, molybdate, oxlate, phosphate or tungstate on ferromagnetic iron powder particles, as per US Patents 6342108, 6340397, 6309748, 6251514, 6129790 and 5982073 claim low core loss in well boded soft magnetic parts made of Fe-P alloys [2, 12, 13, 14, 15, 16]. Post compaction treatment consisting of a heat treatment at a moderate temperature combined with an optional resin impregnation, as per US Patent 5993729 claims an increase in mechanical strength while maintaining low magnetic losses [17]. Electroless plating of controlled quantities of nickel and phosphorous simultaneously onto the surface of carbonyl iron powder, yielding a concentration of phosphorous between 2.0-6.0wt.%; as per US Patent 5963771 claims the possibility of fabrication of intricate parts with various combination of magnetic properties. Further, it is said that the parts suitable for utilization in alternating magnetic fields at different frequencies may be easily fabricated by controlling the concentration of P in ternary Fe-Ni-P composites [18]. Coating of iron powder particles with phosphorous or phosphate and then over-coating the phosphorus coated iron with the thermoplastic or thermosetting insulating organic material, molding of coated particles under pressure and heat to cause organic material to melt and allow the bonding between the coated iron powder particles, and applying a strong magnetic field across the material along a preferred direction of magnetic flux flow during compaction molding; results in orientation of the iron grains in the direction of the magnetic field i.e. the molded composite soft magnetic material with grain alignment, US patent no.5898253 dated April 27, 1999 and US patent no.5693250 dated December 2, 1997 [19]. Coating of the particles of soft magnetic metal sendust (85Fe-10Si-5Al) with a non-magnetic metal oxide (e.g., .alpha-alumina) in a mechano-fusion manner, or heating the particles to form a diffusion layer of .alpha.-alumina thereon, coating the coated particles with a high resistance soft magnetic substance (e.g. ferrite), and sintering the double coated particles under pressure as by hot pressing or plasma activated sintering results in the production of soft magnetic material. It exhibits high saturation induction, magnetic permeability, and electric resistivity. The non-magnetic metal oxide intervening between the soft magnetic metal and the high resistance soft magnetic substance is effective in reducing core loss, US patent no.5348800 dated September 20, 1994 [20]. Mixing, molding and curing (at 180$^o$C for 2 hours) of composition comprising of 70 to 95 vol % of a soft magnetic material (such as spinel ferrite- Mn-Zn ferrite, Ni-Zn ferrite, and Mn-Mg ferrite; and or iron powder, Fe-Ni alloy powder, Fe-Al-Si alloy) powder, with the balance being a liquid thermosetting phenolic resin, results in a molded products of high density, high initial permeability, high strength and dimensional accuracy, US patent no. 4879055 dated November 7, 1989 [21]. A typical method of sintering in reducing atmosphere wherein the pressure in the sintering furnace is maintained between about 0.2-500 Torr and heat treatment for producing sintered stainless steel containing Cr or Mn or at least one alloying element whose standard free energy for oxide formation at 1000$^o$C is 11000 cal/gram or less; results in obtaining high strength, toughness, heat resistance, corrosion resistance, wear resistance, and electromagnetic properties, US patent no. 4614638 dated September 30, 1986 [22]. Further, coating of iron powders with phosphorous; and warm compacting or Ancordense (a patent name) methods are employed to achieve higher sintered density than the value of density achieved in traditional single compacting and sintering operation [11, 23, 24, 25, 26]. The use of coated iron powders with dielectric or insulating organic materials has given a new dimension in the production of P/M ferrous soft magnetic materials with very low core losses [6, 8, 24, 27, 28].

## CONCLUSION

In the summary, powder forging route offers a good scope for enhancing density of parts made from a) electrolytic grade of iron powder, b) binary Fe-P alloy powders, c) ternary Fe-P-Cr and Fe-P-Si alloy powders. Laminations have been easily prepared from these alloy systems and at the same time magnetic characteristics are enhanced or maintained. Raw materials used for the preparation of Fe-P based alloys do not required any special processing technique. Good mechanical properties obtained in Fe-P, Fe-P-Cr and Fe-P-Si alloy systems are additional bonus.

Laminations of Fe-P based powder alloys could be obtained with the similar magnetic characteristics as that of wrought Fe-Si systems. Fe-P-Si alloy powder system is magnetically more isotropic and therefore it does not require preferred texture formation as is necessary in Fe-Si systems. Electrical resistivity of Fe-P-Si powder system is of the same order as that of Fe-Si wrought systems, which make them suitable for applications involving high frequency AC and DC electrical devices.

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