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P/M Processed Fe-Ni Alloys for Soft Magnetic Applications

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ABSTRACT

Pure elements do not possess all the desired properties, both magnetic and nonmagnetic, to meet the manifold requirements for industrial applications. Thus there is an ample scope for property improvement by alloying and other metallurgical means. Alloying of the material primarily increases the resistivity. Nickel addition to iron exerts pronounced effects on nearly all basic magnetic properties. Fe-Ni alloys are known for their high saturation magnetization, resistivity, permeability, low coercivity and good corrosion resistance. The nanocrystalline Fe-5 wt% Ni+0.7 wt% resin soft magnetic composite shows electrical resistivity as high as 520 μΩcm and loss factor of 1Ω/μH at such a high frequency of 1MHz. Molybdenum enhances the permeability of Ni-Fe alloy. These alloys have numerous applications in the clocks, watches and automobile pistons, as absolute standards of length, in rod and tape form for geodetic work and as thermostatic strips.

Keywords: Fe-Ni Alloys; Permeability; Processing

INTRODUCTION

Magnetic materials play a key role in designing electrical and electronic devices. For this reason, the material and its design are important to control smooth running (performance) and minimum energy conversion loss (efficiency) of the device. Only nine elements exhibit ferromagnetism out of a total of 106 elements in the periodic table. All are metals, of which three (Fe, Co and Ni) are 3d transition metals forming the iron-group and other six (Gd, Tb, Dy, Ho, Er and Tm) are lanthanides. Powder Metallurgy (P/M) processing makes it possible to tailor the magnetic properties of the parts to suit specific applications by effectively controlling the material's chemistry and processing parameters. In addition, it utilizes the material to a greater extent and it produces near net shape components directly without going for complex machining sequences. Thus P/M processing provides the product designers a wide flexible range of magnetic materials that covers both DC and AC applications.

LITERATURE REVIEW

Fe-Ni alloys are well known for their valuable properties such as very low thermal expansion characteristics (Fe-36% Nickel alloy, known as Invar) making them suitable for length measuring devices; shape memory (due to its martensitic transformation features) where the alloys when shaped in one state of phase will remember it even after phase transformation; excellent corrosion and creep resistance at elevated temperatures. These alloys also possess good magnetic characteristics. The addition of nickel to iron exerts pronounced effects on nearly all basic magnetic properties over the entire composition range. However, Fe-Ni alloys containing 50 to 80%Ni are popular in soft magnetic applications and are known mainly for their outstanding permeability. These alloys possess quite low coercive force. Because of extremely high permeability (30,000-100,000) and very low coercivity (as low as 0.05 Oe), these materials are specified for magnetic applications requiring improved response time such as in audio coils, pulse transformers and high speed relays [1].

Owing to high cost of nickel, Fe-Ni materials are costlier than other commonly used soft magnetic materials. Further, an appropriate final heat treatment is essential with closely controlled (temperature, atmosphere and cooling rate) conditions to secure desired soft magnetic properties [2]. In addition to it, Fe-Ni alloys possess relatively low saturation induction levels of 15 kG as compared to steel having a saturation of 21.5 kG [3].

The phase diagram of Fe-Ni system is shown in the Figure 1 where the magnetic transformation temperatures are also marked. It indicates the presence of α-phase (body centered cubic) and γ-phase (face-centered cubic) over a range of composition, both are ferromagnetic. There is a large thermal hysteresis in the $\alpha \rightarrow \gamma$ and $\gamma \rightarrow \alpha$ transformations because of low diffusion rates below about 500°C and the equilibrium shown in Figure 1 is very difficult to achieve. For example, the $\gamma \rightarrow \alpha$ transformation on cooling is so sluggish that it is easy to obtain 100% γ at room temperature in alloys containing more than about 35%Ni by air cooling γ from an elevated temperature [4,5]. Commercial Fe-Ni magnetic alloys, which are in the range of 50-80%Ni, are all face-centered cubic. The alloy at and near the composition $FeNi_3$ (about 78%Ni) undergoes long range ordering below 503°C [4]. Fe atoms occupy the corner lattice points and Ni atoms occupy face-centered positions of fcc unit cell in the ordered $FeNi_3$ alloy. The magnetic properties of ordered alloys are inferior to those of disordered. Fortunately, disordered to ordered transformation is sluggish and can be easily avoided simply by rapid cooling through the temperature range 500 to 400°C [5].

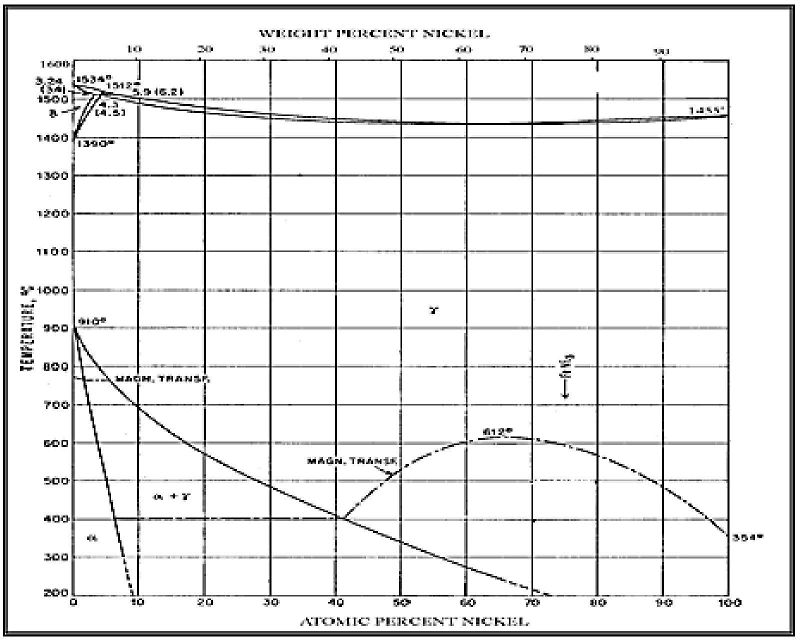

Figure 1: Phase diagram of Fe- Ni system [6]

The magnetic properties of Fe-Ni alloys containing Ni in the range of 65-85% are susceptible to magnetic anneal. The results of magnetic annealing as obtain on 65%Ni-35%Fe alloy are shown in Figure 2. Comparison of the hysteresis loop of Figure 2c with (a) or (b) shows the dramatic effect of magnetic annealing; the sides of the loop become essentially vertical, as expected for a material with a single easy axis. Conversely, if the loop is measured parallel to the hard axis, i.e., at right angles to the annealing field, the sheared-over, almost linear loop shown in (d) is obtained. Alloys which show the magnetic annealing effect commonly have the peculiar, "constricted" loop as shown in Figure 2b when they are slowly cooled in the absence of a magnetic field [5]. The dependence of electrical resistivity upon composition is shown in Figure 3; and for various magnetic properties such as saturation magnetization and Curie temperature in Figure 4. The resistivity reaches a maximum at 36%Ni and the saturation magnetization reaches a maximum value at the equiatomic composition.

Many of the properties of Fe-Ni alloys containing 45 to 90%Ni are greatly sensitive to heat treatment. Following heat treatments viz. Furnace cool, Double Treatment and Bake are designed to study the effect of cooling rates during heat treatment of Fe-Ni alloys on the change in initial permeabilities and maximum permeabilities over the range of composition of Fe-Ni alloys.

A heat treatment known as "Furnace cool" or "Pot anneal", consists of heating to 900-950°C, maintaining at that temperature for about an hour, and cooling at the maximum rate of 100°C per hour. Before this treatment, the specimen is dusted with finely powdered, silica and placed in an iron pot with the cover sealed with a mixture of powdered, low melting glass and powdered iron [4].

The second or the "Double Treatment" consists of heating for 1 hour at 900-950°C and cooling as mentioned above, then heating to 600°C and cooling in the open air by placing on a copper plate at room temperature (or the first cooling to room temperature could be omitted). This procedure is also known as "Permalloy treatment", or "air quench"; the maximum rate of cooling is about 1500°C/min [4].

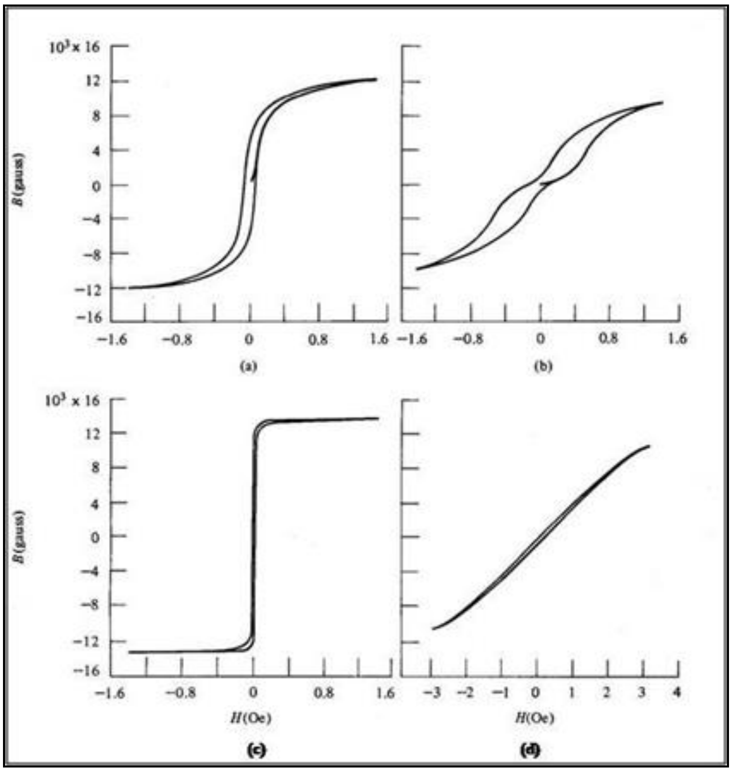

Figure 2: Hysteresis loops of 65Ni-35Fe alloy after various heat treatments: (a) annealed at 1000°C and cooled quickly, (b) annealed at 435°C or cooled slowly from 1000°C, (c) annealed at 1000°C and cooled in a longitudinal field, (d) same as (c) but with a transverse field

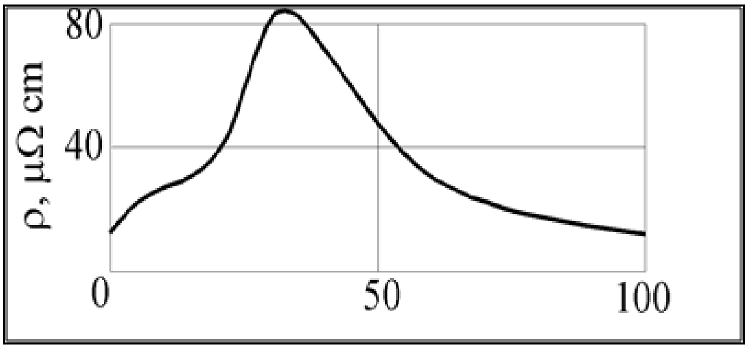

Figure 3: Electrical resistivity of Fe-Ni alloys at room temperature [2]

The third treatment, known as "Bake", the specimen is first heated in a closed pot to 900-950°C and maintained for many hours at lower temperature, usually 20 hours at 450°C. In later experiments the maximum temperature is raised to 1050-1100°C [4]. The results of above treatments are shown in Figures 5a and 5b. The greatest increase in initial permeabilities up to about 10000 is observed for 78% nickel alloy (78 Permalloy) by "double treatment" or "Peralloy treatment" and a similar increase is found in the maximum permeabilities for this alloy, which attained values of over 90,000 as shown in Figures 5a and 5b respectively [4].

The property variation is seen in Figures 3-5 as a function of composition explains why the Fe-Ni system offers three attractive magnetic alloys; (i) about 36%Ni-Fe, known as Rhometal, for maximum resistivity; (ii) 50% Ni-Fe, known as Hipernik, for maximum saturation magnetization and (iii) about 78%Ni-Fe, known as Permalloy, for excellent values of initial and maximum permeabilities. In addition, Isoperm, also at 50%Ni is well known for having constant permeability. Numerous other commercial products with specific characteristics are developed from this binary system and a summary of important commercial Ni-Fe products is given in Table 1, illustrating magnetic properties and applications of these materials. It is interesting to note that Sinimax (54%Fe-43%Ni-3%Si) has high permeability, low coercive force and high resistivity as compared to these properties in 45 Permalloy (55%Fe-45%Ni) having nearly the same Ni content. Thus the addition of silicon has a favorable effect in improving the magnetic properties of the Fe-Ni alloys.

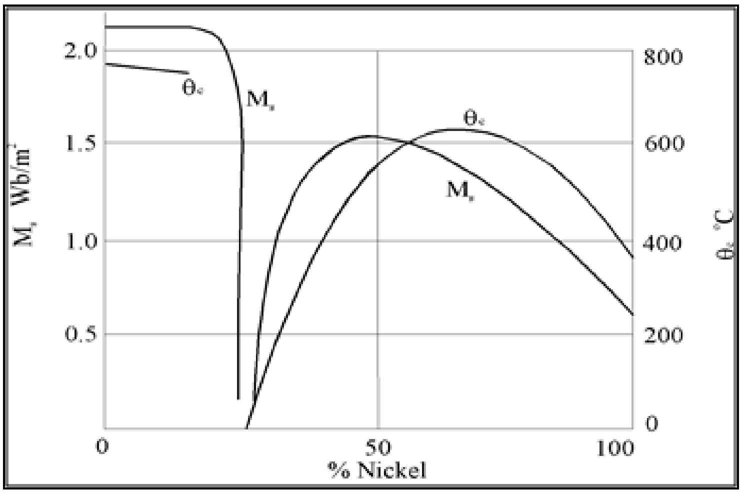

Figure 4: Variation in saturation magnetization and the curie temperature of alloys in the Fe-Ni system [2]

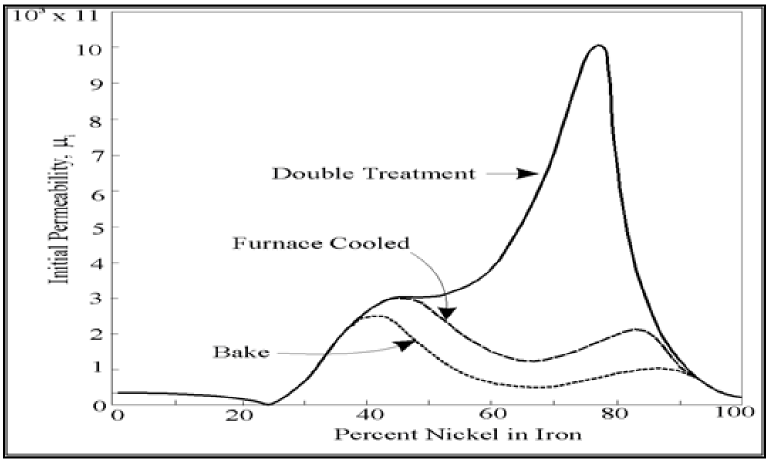

Figure 5a: Composition dependence and effect of heat treatment on initial relative permeability of Fe-Ni alloys [4]

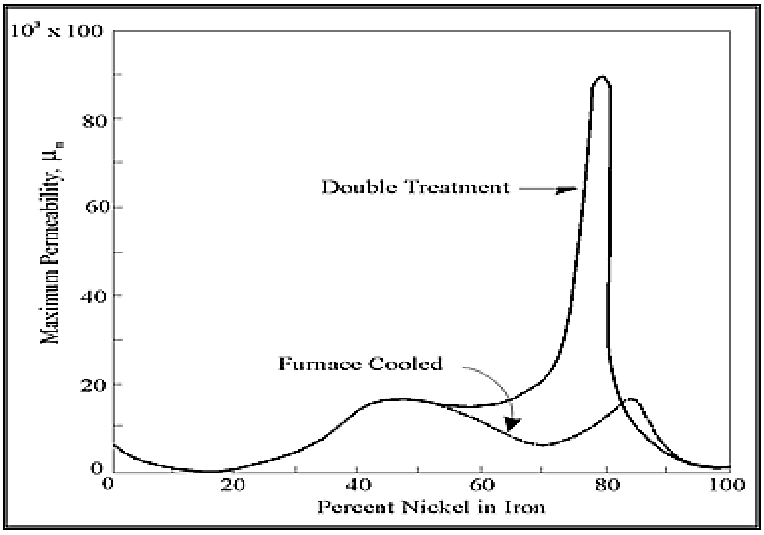

Figure 5b: Composition dependence and effect of heat treatment on maximum relative permeability of Fe-Ni alloys [4]

Table 1: Magnetic properties of Ancor* 50Fe/50Ni material compacted at 415 MPa and 690 MPa and sintered at 1120°C and 1260°C [3]

Sintering temperature (°C)	Compaction pressure, MPa (tsi)	Sintered density (g/cm^3)	H_C (Oe)	B_r (kG)	B_{max} (kG)	μ_{max}
1120	415 (30)	6.9	0.57	4.6	8.6	4730
	690 (50)	7.4	0.58	5.3	10.9	5430
1260	415 (30)	7.01	0.47	5.5	9.8	7140
	690 (50)	7.5	0.46	6.7	11.8	8910

*Ancor is a registered trademark of Hoeganaes Corporation

Table 2 lists typical magnetic properties of a water atomized prealloyed Fe-50%Ni powder compacted at 30 and 50 tsi and sintered for 30 minutes at 1120°C in dissociated ammonia. Despite good compressibility, the majority of commercial Fe-50%Ni P/M components are double pressed/double sintered to densities in excess of 7.4 g/cm^3. Double press/double sintered processing may appear costly [3], however, it is minor when compared to the high raw material cost (approximately ten times of the cost of pure iron).

Alloys of 50Ni/50Fe often require magnetic annealing after the P/M processing to achieve maximum properties. Typical annealing parameters for this material are 1000°C/1070°C for two hours followed by a slow cooling (not to exceed 3°C per minute). The annealing cycle is often substituted for the second sintering cycle in a double press/double sinter process, thus reducing the total processing costs [3]. Prealloyed 50Ni/50Fe material may exhibit the permeability up to 15000 Gauss/Oersted with a coercive force of approximately 0.25 Oersted. Drawbacks to this system are: the high material cost (due to high Ni content), low maximum saturation induction and severe degradation of magnetic properties with minor amounts of cold working or machining [7].

Table 2: Properties and applications of Nickel-Iron wrought alloys [2]

Material	Nominal Composition (%)			Relative permeability		B_s T	B_r T	H_c A·m^{-1} (Oe)	Resistivity 10^{-7} Ω·m	Some characteristics and applications
	Ni	Fe	Others	μ_i	μ_m					
Rhometal	36	64	-	1800	7000	0.9	0.36	26 (0.33)	8.5	High resistivity alloy
Sinimax	43	54	3 Si	3000	50000	1.1		4.8 (0.06)	9	High resistivity, high μ_m ;
Monimax	48	49	3 Mo	2000	35000	1.5		8 (0.1)	8	high frequency coils
45 Permalloy	45	55	-	2500	30000	1.6	0.8	16 (0.2)	5	Good overall characteristics ; high μ_i , μ_m and low losses ; audio transformers, coils, relays
Hipernik	50	50	-	4500	70000	1.6	0.8	4 (0.05)	5	Similar to 45 Permalloy, but more highly purified
Deltamax	50	50	-		150000	1.6	1.45	8 (0.1)	5	Grain oriented in the (001)[100] texture; rectangular hysteresis loop; magnetic amplifiers, coils, contact rectifiers
Isoperm; Conpernik	50	50	-	1500	2000	1.6			5	Constant permeability : chock coils
78 Permalloy	78	22	-	8000	100000	1.07	0.6	4 (0.05)	1.6	High μ_i, low H_c and low B_r; sensitive dc relays
4-79 Mo-Permalloy	79	16	5 Mo, 0.5 Mn	20000	100000	0.87	0.5	2.4 (0.03)	5.5	Very high μ_i, low losses; audio coils, transformers, magnetic shields.
Supermalloy	79	15	5 Mo, 0.5 Mn	75000	800000	0.8	0.5	0.48 (0.006)	6	Highest μ_i ; low losses; high efficiency ac coils, pulse transformers and magnetic amplifiers and magnetic amplifier coils.
Mumetal	77	16.5	5 Cu, 1.5 Cr	20000	100000	0.65	0.3	4 (0.05)	6	Similar to 4-79 Mo-Permalloy and has good ductility; cores of current transformers; in radio apparatus at audio frequency, for magnetic shielding, and in low level magnetic amplifiers.

CONCLUSION

Iron (in the temperature range of 910°C to 1400°C) and nickel exist in fcc lattice, form solid solutions at room temperature or above the pertinent phase transition temperature. When iron is alloyed with Ni, the γ- phase field will be opened up by suppressing the other α- phase. The two primary solid solutions emerge with a two-phase region lying in the middle at temperature around 20°C in each system. While developing these alloys, the primary concern is the solubility limit of the solute that is the maximum percentage of the solute that can be dissolved completely in the solvent. Once the solubility limit is known, a proper procedure can be devised to ensure the preparation of an alloy in a single-phase state.

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