Microstructural and Magnetic Properties of Fe-Mn-Al Soft Magnetic Alloys

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Magnetic properties of Fe-Mn-Al alloys containing 1.0 mass% Al and 0.5–2.0 mass% Mn have been evaluated. The hot rolled alloys after annealing at 750–800°C have shown high induction, high remanence, low coercive force and reasonably high permeability. The annealed alloys have exhibited high tensile strength (335–345 MPa) and high elongation (30–40%). The d.c. electrical resistivity of the alloys have been found to be in the range $20\text{--}22 \times 10^{-8} \Omega \cdot \text{m}$. Microstructural studies of the alloys have also been made and correlated with the magnetic properties.

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I. Introduction

The commercial class of soft magnetic materials comprises of iron, low-carbon steel, iron-silicon alloys, iron-aluminium and iron-aluminium-silicon alloys, iron-nickel alloys, iron-cobalt alloys and soft ferrites. On the basis of consumption, iron-silicon alloys are by far the widely used magnetic materials. The iron-silicon alloys containing 3.0–4.0% Si have resistivities in the range $45\text{--}55 \times 10^{-8} \Omega \cdot \text{m}$ and can be employed in both a.c. and d.c. applications. Whereas the more sophisticated cold rolled grain oriented (CRGO) silicon steels are used for large generators and power and distribution transformers. The non-oriented silicon steels are generally employed in small motors and generators, small power transformers and relays. Commercially pure iron has low resistivity ($10\text{--}15 \times 10^{-8} \Omega \cdot \text{m}$) and is used in electromagnet cores and some relays. Iron-nickel alloys have nickel ranging from 36 to about 79 mass% and are expensive. They are used in high frequency power and current transformers, motors and generators, magnetic amplifiers, sensitive relays and telephone receivers, magnetic shielding, loading coils, etc.

With a view to developing new soft magnetic alloys for applications in relay cores, studies have been made on alloys containing 1.0 mass% Al, 0.5–2.0 mass% Mn and balance iron (low carbon). The effect of addition of Al is more or less the same as that of Si in decreasing the saturation induction and in increasing the electrical resistivity⁽¹⁾⁽²⁾. In addition, Al helps in grain coarsening⁽³⁾⁽⁴⁾ and consequently in the improvement of magnetic properties. Manganese addition, besides reducing the oxygen content is also known to improve hardenability and tensile strength⁽⁵⁾⁽⁶⁾ and to increase the grain size⁽⁷⁾.

II. Experimental

Three alloy compositions were made (Table 1) by melting low carbon iron (C 0.03–0.04%), electrolytic manganese (of purity 99.92%) and aluminium (of purity 99.5%) in a high frequency induction furnace and casting in cast iron moulds. The ingots were homogenised at 1200°C for 2–3 h and hot forged and hot rolled from 1150°C to a thickness of about 2–3 mm. Toroid specimens made out of hot rolled sheets were tested for their magnetic properties using Walkers MH-3020 Hysteresisgraph. The magnetic properties were also determined after annealing the toroid specimens at 750, 800, 850, 900 and 950°C for 3 h. The mechanical properties, viz., hardness, tensile strength, yield strength (YS) and elongation of the annealed specimens were also determined according to ASTM specification. Microstructural (optical microscopy) studies were made on as-hot rolled as well as annealed samples. Electrical resistivity measurements were performed using Kelvin double bridge.

III. Results and Discussions

The microstructures of the alloys are presented in Figs. 1–3. It is interesting to see the variation in grain sizes of the three alloys. Alloy No. 1 has shown the largest while alloy No. 3 the smallest. Studies by Boc and Crof⁽³⁾ on non-oriented silicon steel have shown that small amounts of Al addition results in grain coarsening. In low carbon

Table 1 Nominal composition of the alloys (all in mass%).

Alloy No.	Mn	Al	C	Fe
1	0.5	1.0	0.03	balance
2	1.0	1.0	0.04	balance
3	2.0	1.0	0.04	balance

Fig. 1 Microstructures of Alloy No. 1, annealed at (a) 750°C (b) 800°C, (c) 850°C, (d) 900°C and (e) 950°C, for 3 h showing coarsening of the grains with increase in the annealing temperature.

steels, Mn addition has also been found to give rise to large grains⁽⁷⁾. Marked grain coarsening has been observed in case of Alloy No. 1. At higher annealing temperatures, grain size has increased to a considerable extent (Fig. 1(d) and (e)). In Alloy No. 2 and Alloy No. 3, the grain coarsening effect of Al is absent and there is almost no change in the grain size of Alloy No. 3 with respect to the annealing temperature.

The magnetic properties of the as-hot rolled and annealed alloys are given in Table 2 and Figs. 4–6. The as-hot rolled alloys are characterised by low remanence (Br), high coercive force (Hc) and low permeability (μ_{max}) as compared to the annealed alloys. The magnetic induction (B) values at 4, 8 and 12 kA/m are more or less the same in both the hot rolled and annealed alloys. Saturation

magnetisation being a structure insensitive property, one would expect, particularly at higher fields, the same induction values for the as-hot rolled and annealed alloys. The highest induction value of 1.92 T at 12 kA/m has been observed in case of Alloy No. 1 and the lowest for Alloy No. 3 (1.84 T). This is reasonable since the induction values decrease with increasing percentage of non-magnetic alloying elements namely Mn and Al. Remanence (Br) unlike saturation induction, is a structure sensitive property and is expected to change whenever changes in the crystalline or domain orientations are introduced through annealing, magnetic annealing etc. The annealed alloys, in fact, have shown a significant improvement in remanence as compared to the Br of the as-hot rolled alloys. The drop in Hc after annealing

Fig. 2 Microstructures of Alloy No. 2, annealed at (a) 750°C, (b) 850°C and (c) 950°C, for 3 h. The increase in grain size from (a) to (c) is only marginal.

Fig. 3 Microstructures of Alloy No. 3, annealed at (a) 750°C, (b) 850°C and (c) 950°C, for 3 h, indicating almost no change in the grain size.

Table 2 Magnetic, mechanical and electrical properties of Fe-Mn-Al alloys.

Property	As hot rolled			Hot rolled, annealed at 800°C for 3 h		
	Alloy 1	Alloy 2	Alloy 3	Alloy 1	Alloy 2	Alloy 3
Mag. Induction at 8 kA/m (T)	1.86	1.82	1.78	1.82	1.80	1.77
Mag. Induction at 12 kA/m (T)	1.94	1.90	1.85	1.92	1.88	1.84
Remanence (T)	0.96	0.98	0.87	1.32	1.47	1.44
Coercive force (A/m)	322	420	438	66	103	111
Relative Max. permeability ($\mu_{\max}$)	1150	950	780	10400	7000	5528
Resistivity ($\times 10^{-8} \Omega \cdot \text{m}$)	25	27	27	21.6	21.8	21.2
Hardness (VPN)	190	215	255	83	86	94
UTS (MPa)	..	..	..	344	336	341

Fig. 6 Magnetic properties of Alloy No. 3.

Fig. 4 Magnetic properties of Alloy No. 1.

Fig. 5 Magnetic properties of Alloy No. 2.

the hot rolled alloys is substantial. This is attributed to the stress relief and to the grain size effects, larger grains giving rise to smaller values of H_c .

The effect of grain size on coercive force (H_c) is evident when one looks at Figs. 4–6. In case of Alloy No. 1, the coercive force has shown a decreasing trend with increasing annealing temperature indicating that larger grain size results in lower H_c . However, for Alloy No. 2 and Alloy No. 3, the change in the grain size with respect to annealing temperature is insignificant and this has resulted in an almost constant value of H_c (Figs. 5 and 6). The permeability changes in these alloys corresponding to different annealing temperatures are, more or less, as expected. As the coercive force has decreased with increasing annealing temperature, the permeability has shown an increase, for Alloy No. 1. However, in the case of Alloy Nos. 2 and 3, the changes in permeability values are very small.

A striking feature of Alloy No. 1 is the decrease in coercive force, increase in permeability and almost no change in the magnetic induction values as the annealing temperature is increased from 750 to 950°C.

The mechanical properties of the alloys are also given in Table 2. The alloys have shown reasonably good strength (UTS ~ 340 MPa) and hardness (83–94 VPN). The alloys have shown electrical resistivity of $21\text{--}22 \times 10^{-8} \Omega \cdot \text{m}$, which are much higher compared to that of low carbon iron. Alloying iron with Al is known to increase the resistivity in a similar way as silicon does in silicon steels.

Of the three alloys studied, Alloy No. 1, in particular, has shown promise for use in relay core applications. The magnetic induction and permeability of this alloy have been found to be either better or comparable to low carbon iron and 4% silicon steel. The coercive force of this alloy, however, is slightly on the higher side. The increase in coercive force of the alloy has been found to be only 5–6%, after aging at 100°C for 100 h, which is within the acceptable limit.

IV. Conclusions

The improvement in structure-sensitive magnetic properties such as permeability and coercive force in low carbon steels/iron alloys can be brought about by the evolution of suitable microstructures. Generally, large grained structure gives rise to superior magnetic properties. The present study has shown that:

(i) At low Mn content, the grain coarsening effect of Al is maximum in Fe-Mn-Al alloys. The contribution from Mn to grain coarsening may also have to be carefully looked into.

(ii) Effect of annealing temperature on the grain size and the magnetic properties is marked in Alloy No. 1. Also, the magnetic properties are superior in case of Alloy No. 1.

(iii) Average grain size of $\sim 120 \mu\text{m}$ gives rise to superior properties in Fe-Mn-Al alloys.

(iv) The magnetic properties of the alloys are com-

parable to low carbon iron and silicon steels.

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