Effect of Inclusion Content on Magnetic Properties of Soft Magnetic Iron-Cobalt-Vanadium Alloy for Aerospace and Aeronautical Applications

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ABSTRACT

Soft magnetic alloys constitute an important class of engineering materials since it can easily be magnetized and demagnetized with a small external field. They are ideally suited for applications requiring high flux density and reduction in weight specifically for aeronautical and aerospace applications. Melting this alloy needs special attention due to inclusion arising from the refractory of the vacuum Induction melting furnace or any other impurity coming from the deposit of the previous heat. These types of inclusions reduce the magnetic properties drastically. A detailed study was conducted from different industrial heats taken and the variation of magnetic properties was analyzed. The inclusion content in different heats was studied using scanning electron microscope and energy dispersive X-Ray. The study results revealed that distribution of inclusion content has a pronounced effect on magnetic properties.

Keywords—Soft Magentic alloys; High Flux Density; Inclusion Content; Vacuum Induction Furnace

I. INTRODUCTION

Metallic soft magnetic alloys have high permeability, low coercivity, low loss and excellent formability. Iron cobalt soft magnetic alloy (49Co-49Fe-2V) gives a combination of very high saturation flux density (2.2 Tesla) combined with moderately high permeability (around 8000) and high strength [1]. Processing of this alloy poses a great challenge mainly due to ordering transformation that makes the alloy brittle at room temperature and cold rolling is very difficult to make thin strip whereas ordering is essential to get better magnetic properties [2]. These alloys are mostly used as rotor of main propulsion of aircraft engine and, torquer rod in space vehicle [3,4]. In order to stop ordering transformation during processing (to facilitate cold working) 2% Vanadium is added in this alloy which delays the ordering transformation during cooling but also lowers the permeability and saturation flux density slightly and, increases the coercive force marginally [5].

Table 1 Chemical analysis of the heats of 49Co-49Fe-2V alloy

Parameter	Heat-1	Heat-2	Heat-3	Heat-4	Heat-5	Specified Value
Cobalt (Wt.%)	49.7	49.6	48.9	48.5	48.5	48.5-49.0
Iron (Wt.%)	Balance	Balance	Balance	Balance	Balance	Balance
Vanadium (Wt.%)	1.7	2.1	2.0	1.8	2.1	1.7-2.2
Carbon (Wt.%)	0.005	0.004	0.003	0.005	0.008	0.005
Sulphur (Wt.%)	0.002	0.003	0.002	0.004	0.005	0.004
Phosphorus (Wt.%)	0.004	0.005	0.004	0.003	0.002	0.005
Oxygen (PPM)	10	15	15	18	20	Not specified
Permeability	4500	6800	9500	5200	7100	7000

Table 2. Steps followed for processing 49Co-49Fe-2V alloy

1	Melting in vacuum Induction melting furnace
2	Forging to 60 x 260 mm slab
3	Machining to 50 x 240 mm slab
4	Hot rolling to 2.5 x 250 mm
5	Quenching in ice-brine solution to stop ordering
6	Cold rolling to 0.3 mm strip
7	Heat treatment of samples at 850 °C for 3 hrs. followed by cooling at a rate of 80 – 120 °C/hr. up to 200 °C in hydrogen atmosphere
8	Testing for magnetic properties

Table 3. Property values obtained in various heats

Property	Specified Values	Obtained Values
Saturation Flux Density (Tesla) should be as high as possible	2 (min.)	2 to 2.2
Coercive Force (Oes) (should be as low as possible)	1 (max.)	0.9 to 1.4
Permeability (nominal) (should be as high as possible)	7000	4500 to 9000

II. METHODOLOGY

Several heats in commercial scale (2.2 Tons melt size) were taken in vacuum furnace. The processing steps followed are listed in table 2. After characterization permeability was observed and found to be varied from 4500 to 9500 and coercive force between 0.9 to 1.4 Oes, with change in saturation flux density from 2 to 2.2 as specified in table 3. The unexpected behavior of this alloy was investigated. The probable reasons for abnormal variation of magnetic properties can be attributed to one of the following reasons.

- Abnormal change in chemistry of the alloy during melts which increases the anisotropy constant thereby reducing permeability and increasing coercive.
- Refractory condition of the furnace resulting in introduction of excessive inclusion content obstructing domain movement thereby reducing magnetic properties.
- Melting practice followed in vacuum induction furnace which may result in more inclusion content.
- Hot or cold processing of the alloy.
- Heat treatment followed on samples which can introduce fine grains or disordered structure and thereby reducing magnetic properties.

The various processing parameters and steps involved were carefully examined as mentioned in the following sections.

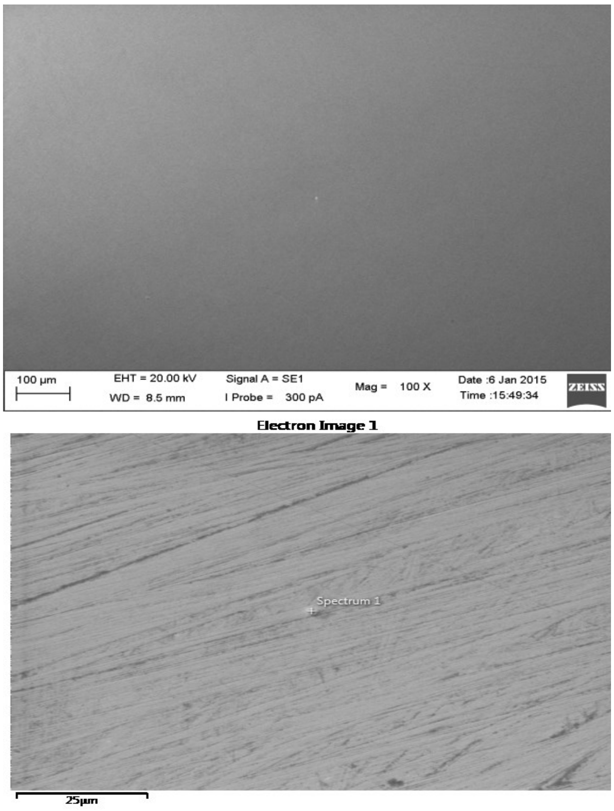
A. Chemistry of the different heats taken

Chemistry of the alloy plays a very important role in determining the magnetic properties. Main elements in the alloy is cobalt, Iron and Vanadium which determine the anisotropy constant and had effect on magnetic properties. Other trace or trump elements such as carbon, sulfur, phosphorus also effect the magnetic properties by forming inclusions like carbides, sulfides, and phosphides etc. which inhibits the domain movements of the alloy and reduces the magnetic properties. The chemical analysis of all the five heats taken were reanalyzed on the final cold rolled strips using optical emission spectrometer and the results are shown in table 1. The chemical analysis shown in the table 1 indicates that chemical composition is well controlled and is very much within the specified limit. Even deoxidation was carried out, carbon-oxygen reaction and carbon coming from the raw material was steadily reduced to the specified level. Deoxidizers like aluminum and silicon were not used in any of the heats to reduce the solid oxide inclusion so that domain movement is not hindered. The source of raw materials were similar so that chances of variation of any other trace or trump elements is reduced. Total melting time was between 4 to 5 hours for all the heats. The above analysis indicates the chemical composition and melting practice followed for all the five heats were within the specified limits and may not have affected the magnetic properties.

B. Hot and cold processing carried out

After melting in vacuum induction melting furnace the liquid metal is cast in the form of ingot in argon atmosphere and is subjected to hot and cold working. The ingots are forged to 50 x 250 mm slabs and subsequently hot rolled to 3 mm strip. Immediately after hot rolling the strips are quenched in ice brine solution to avoid ordering. Ordering makes the alloy brittle and subsequent cold rolling is not possible. This step is very critical.

Once the alloy is made to disordered state, cold rolling is carried out. The disordered structure is so ductile that it can be cold rolled to 0.3 mm thickness [3]. Normally hot rolling and hot forging do not have any effect on magnetic property. But the amount of cold rolling is important for attainment of final grain size after annealing to achieve the magnetic property. As strips of all the heats were cold rolled from 5.0 mm to 0.3 mm (cold reduction given was 90%), so the effect on previous cold reduction of final grain size were same and it was observed in the microstructure of all the heats. The grain size was around ASTM No. 2-3 for all the heats, so it can be concluded that hot or cold working have not contributed to variation in magnetic properties.



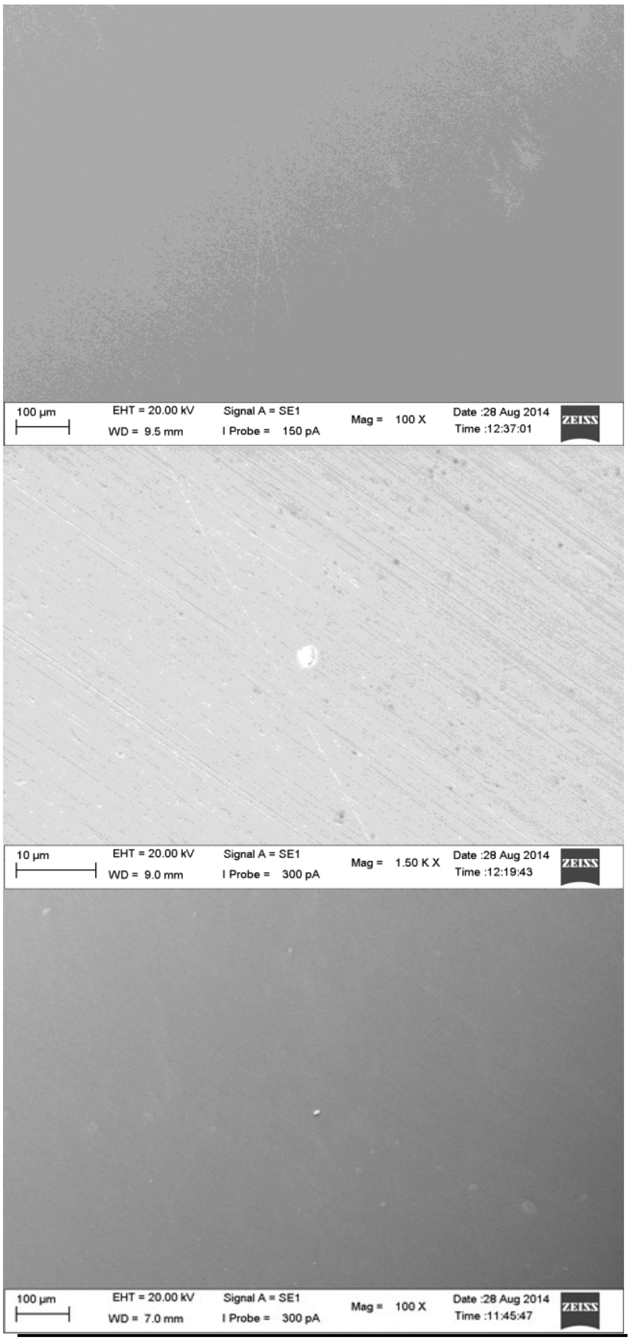
Best Permeability Sample	
Particle Size	No. of Particles (Area Scanned at 100X & 2000X, >20 Nos.)
<2µ	1
3-6 µ	-
7-10 µ	-

Fig. 1. Visibility of Inclusions in 9500 permeability sample

C. Heat treatment to achieve properties

Once the strip has been rolled out to 0.3 mm thickness, rings of 30 mm OD and 20 mm ID are punched out, edge burrs are removed and final heat treatment is carried out to remove the stresses generated during processing and to develop ordered structure which is essential to get good magnetic properties.

Annealing cycle followed is heating to 825 °C for 3 hours followed by cooling at a rate of around 100 + 20 °C / hr. up to 200 °C (below order-disorder transformation temperature) followed by furnace cooling till 50 °C. The whole heat treatment is carried out in hydrogen atmosphere to protect the surface from oxidation and to reduce carbon and sulphur content of the strip. The cooling was controlled by a PLC and regulating the flow rate of hydrogen during cooling. As the cycle may not be uniform if done separately for five heats, samples from all the five heats were heat treated in one cycle so that the possibility of variation of heat treatment can be ruled out. The above processing details revealed that none of the factors i.e. variation of chemistry, hot or cold processing and, heat treatment did not have much effect on the change of magnetic properties.



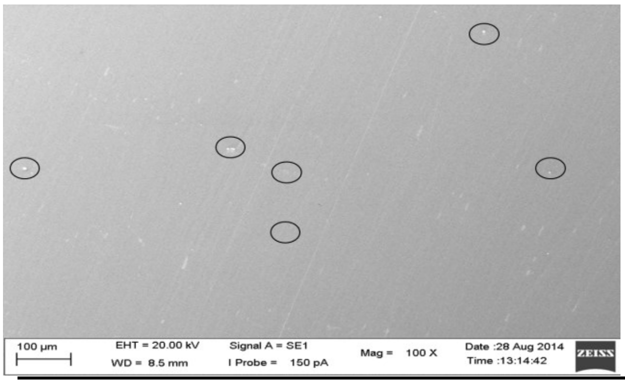
Good Permeability Sample	
Particle Size	No. of Particles (Area Scanned at 100X & 2000X, >20 Nos.)
<2µ	4
3-6 µ	-
7-10 µ	-

Fig. 2. Visibility of Inclusions in 7100 permeability sample

D. Metallographic Study of Heat Treated Samples

To estimate the inclusion content in the material which comes during melting because of lining condition and previous history of melting, the microstructure, inclusion content and types were analyzed using scanning electron microscope (SEM) and energy dispersive X-Ray analysis (EDAX). The melt history records (log sheets of melting) were studied.

Fig. 1 shows the visibility of inclusions in 9500 permeability sample. The No. of inclusion is 1 and the type is magnesium oxide. This heat was taken after lining the vacuum furnace crucible with MgO and Al2O3 followed by taking wash heat of pure iron (fresh heat), so only one inclusion from the lining was noticed in the structure. There was no contamination of lining and the lining structure was quite stable. Fig. 2 shows the Visibility of Inclusions in 7100 permeability sample. The No. of inclusions noticed was 4 and type of inclusion was Alumina and magnesia.



Lowest Permeability Sample

Area No.	Less than < 2 µ	3-6 µ	7-10 µ
1	2	2	2
2	-	1	1
3	-	-	1
4	-	1	-
5	6	-	-
6	1	-	-

Fig. 3 Visibility of Inclusions in 4500 permeability sample

This heat was taken after relining of the crucible and wash heat taken was pure iron (reused once, not first time) may be the deoxidation during previous melting, Al was used to de oxidize which got entrapped in the lining of the furnace and during subsequent melting of the alloy, Al2O3 has come out of the inning and got entrapped in the heat. Fig. 3 shows the Visibility of Inclusions in 4500 permeability sample. The No. of inclusions noticed was 15 and types of inclusions were compound of Cr-Al-Mg. This heat was taken in an old lining where a super alloy containing Cr-Al was taken earlier and subsequently washed with a pure iron heat and melting of 49Co-49Fe-2V heat was taken. The refractory lining of the furnace absorbed the super alloy, has come out from the refractory and got entrapped in the liquid and metal during subsequent melting of Fe-Co-V alloy showed more number of inclusions. As the number of inclusion increase, the movements of domains get pinned up and rotation with applied field coil becomes difficult resulting in lower magnetic properties i.e. low permeability.

III. RESULTS AND DISCUSSIONS

It has been observed from SEM study that the heats showing very good permeability has less number of inclusions whereas the magnetic properties (permeability) deteriorated with increase in inclusion content as shown in Fig. 4. Therefore it can be assumed that, as the number of inclusion increases, the domain movement after applying magnetic field is hindered due to inclusion content resulting in lower permeability and higher coercive force.

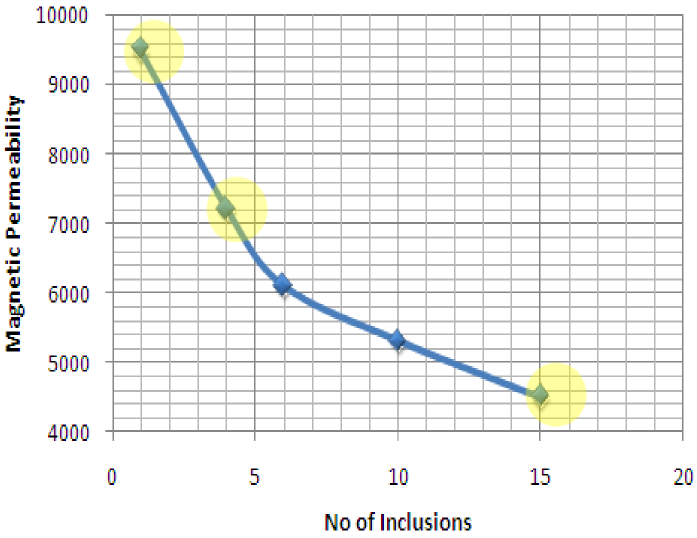
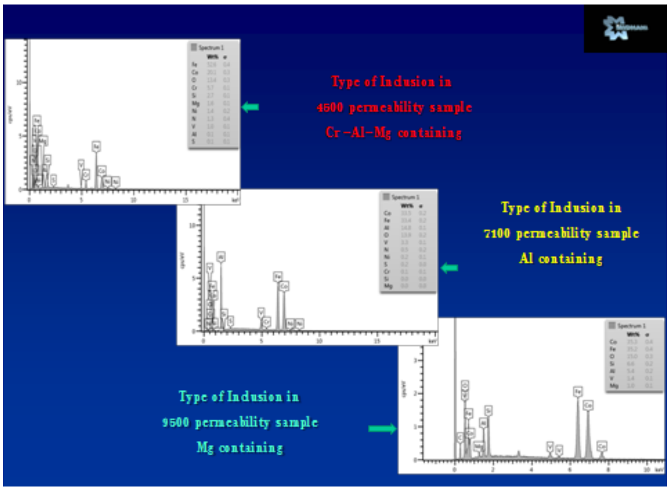


Fig. 4 Magnetic permeability Variation with no. of inclusions


Type of Inclusion in
4600 permeability sample
Cr –Al–Mg containing

Type of Inclusion in
7100 permeability sample
Al containing

Type of Inclusion in
9500 permeability sample
Mg containing

Fig. 5 EDAX Result of the inclusions

It also matches well with the theoretical estimation that lesser is the inclusion content, higher is the permeability [6].In order to find out the origin of the more inclusion content, EDAX analysis of the inclusion content were carried out. Fig. 5 shows the result of EDAX analysis. It was observed that the inclusion of the heat giving lowest magnetic property were complex compound of Ni and Cr. As the alloy does not contain any nickel and chromium, these inclusions are exogenous inclusion which might have come from the refractory lining in the vacuum induction melting furnace.

IV. CONCLUSIONS

- From the above results, It is clear that apart from maintaining the correct process parameters, melting furnace condition is quite important to get good magnetic property and the following care should be taken.
- For Melting magnetic alloy, fresh furnace lining has to be made followed by taking wash heat of fresh heat of pure iron.
- No heat of Fe-Co-V alloy should be taken, if the previous heat is an alloy which contain any elements other than Fe-Co-V
- Melting time should be as low as possible, higher the melting time, more erosion of refractory lining will take place causing more number of inclusions in the melt.
- In this alloy, de-oxidation process to be followed is only by carbon-oxygen reaction because it does not leave any residue in the melt and causes less number of inclusions. Deoxidizers Al and S should not be

used preferably.

Nomenclature

Wt. : Weight
µ : Micron
min. : Minimum
max. : Maximum
PPM : Parts per million
Oe : Oersted
PLC : Programmable logic controller

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